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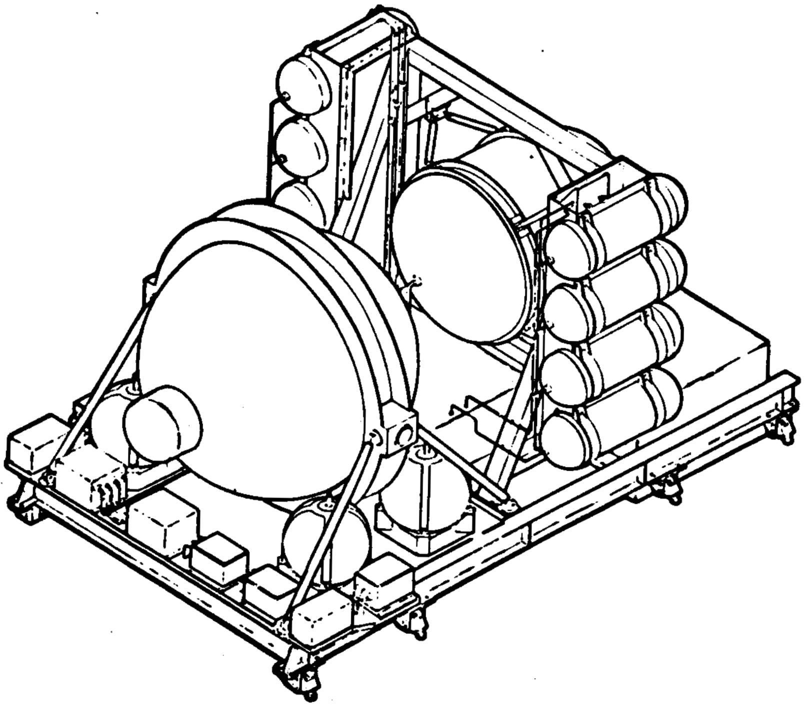
# CRYOGENIC FLUID MANAGEMENT FACILITY CONCEPT DEFINITION STUDY (CFMF)


R.N. EBERHARDT, J.P. GILLE, W.J. BAILEY
AND R.L. BERRY




MARTIN MARIETTA DENVER AEROSPACE



CONTRACT NAS3-23355

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DECEMBER 1983

BY


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16. Abstract

This report documents the results of the Task I - Conceptual Definition activity which forms a basis for the subsequent detailed design of the Cryogenic Fluid Management Facility (CFMF). NASA and DOD mission plans were reviewed to identify in-space cryogenic fluid management requirements, which were then categorized and prioritized to establish recommended systems/technologies for potential study in the CFMF. Analysis of each unique fluid management system, including scaling analysis where appropriate, was performed, and experimental parameters, mission objectives, and preliminary timelines and schematics were formulated for three missions of the CFMF. CFMF/carrier configuration trade studies were performed considering the Spacelab pallet, the MPESS and the MDM pallet carriers. A ROM cost and schedule for development and the three-flight program (first flight assumed mid-1987) was prepared, with emphasis on cost drivers which might influence selection of the preferred carrier.

The recommended conceptual design consists of the CFMF mounted on an MDM pallet (mixed cargo carrier), with the Cryogenic Fluid Management Experiment (CFME) tank assembly (NASA CR-165495) as the supply tank and the following receiver tanks (scaled to Boeing space-based OTV with Aeroassist - NASA CR-3535):

Mission 1 - 0.28 scale, without acquisition device
Mission 2 - 0.18 scale, without acquisition device
Mission 3 - 0.18 scale, with partial acquisition device

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## FOREWORD

This report was prepared by Martin Marietta Corporation, Denver Aerospace, under Contract NAS3-23355. The contract is being administered by the Lewis Research Center of the National Aeronautics and Space Administration, Cleveland, Ohio . The report documents the results of Task I - CFMF Conceptual Definition.

The following NASA-LeRC individuals are involved in the CFMF Detailed Design program:

Mr. Erich W. Kroeger - Project Manager
Mr. John C. Aydelott - Principal Investigator
Mr. Eugene P. Symons - Overall Program Management

In addition to the authors the following Martin Marietta personnel contributed to the Task I effort:

Mr. John S. Marino - Design
Mr. William A. Johns - Thermal and Fluid Analysis
Mr. Sam M. Dominick - Cryo Fluid Management Technical Requirements, Receiver Tank Partial Acquisition Device Analysis and Conceptual Design
Mr. Carl D. Sterling - Thermal Integration Design Trades
Mr. Glenn E. Hitchcock - Avionics; control and Data Acquisition System
Mr. Nevin E. Fornwalt - Avionics; Control and Data Acquisition System
Mr. Dale A. Fester - Fluid Management System and Conceptual Design Review

The data in this report are presented with the International System of units as the primary units and English units as secondary units. All calculations and graphs were made in English units and converted to the International units. Some requirements (primarily dimensions and displacements), specified in handbooks and Interface Control Documents in English units only, are likewise presented in English units only in this report.

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## ABBREVIATIONS AND ACRONYMS

| | |
|---|---|
| BTU | British Thermal Unit |
| C | Centigrade |
| CADS | Control and Data Acquisition System |
| CDR | Critical Design Review |
| CFME | Cryogenic Fluid Management Experiment |
| CFME-TA | Cryogenic Fluid Management Experiment - Test Article |
| CFMF | Cryogenic Fluid Management Facility |
| cm | Centimeter |
| CSAM | Cryogenic Storage Analysis Model |
| D | Diameter |
| DA | Double Amplitude |
| DACS | Data Acquisition and Control System |
| db | Decibel |
| DC | Direct Current |
| DOD | Department of Defense |
| DTR | Data Tape Recorder |
| EGSE | Electrical Ground Support Equipment |
| ESA | European Space Agency |
| ET | External Tank |
| F | Fahrenheit |
| ft | Foot |
| FMDM | Flexible Multiplexer/Demultiplexer |
| g | Force of Gravity |
| GHe | Gaseous Helium |
| GHz | Giga Hertz |
| GH2 | Gaseous Hydrogen |
| GMT | Greenwich Mean Time |
| GSE | Ground Support Equipment |
| GSFC | Goddard Space Flight Center |
| Hr | Hour |
| HX | Heat Exchanger |
| Hz | Hertz |
| in | Inch |
| I/O | Input/Output |
| K | Kelvin |
| kg | Kilogram |
| kHz | Kilo Hertz |
| km | Kilometer |
| kN | Kilo Newton |
| KSC | Kennedy Space Center |
| L | Length |
| LAD | Liquid Acquisition Device |
| lb | Pound |
| lbm | Pound Mass |
| LeRC | Lewis Research Center |
| LH2 | Liquid Hydrogen |
| LN2 | Liquid Nitrogen |
| m | Meter |
| MDM | Multiplexer/Demultiplexer |
| MET | Mission Elapsed Time |

ABBREVIATIONS AND ACRONYMS (CONTINUED)

| | |
|---|---|
| MHz | Mega-Hertz |
| min | Minute |
| MLI | Multilayer Insulation |
| MPESS | Multipurpose Experiment Support Structure |
| MSFC | Marshall Space Flight Center |
| N | Newton |
| NASA | National Aeronautics and Space Administration |
| OCP | Operation Control Panel |
| Oct | Octive |
| OFT | Orbital Flight Test |
| OMV | Orbit Maneuvering Vehicles |
| OPF | Orbiter Processing Facility |
| OTV | Orbit Transfer Vehicles |
| PCB | Power Control Box |
| PDU | Power Distribution Unit |
| PDR | Preliminary Design Review |
| PL | Payload |
| PPIH | Payload Pallet Integration Hardware |
| PPM | Parts Per Million |
| psi | Pound per Square Inch |
| psia | Pound per Square Inch Absolute |
| psig | Pound per Square Inch Gage |
| PTB | Paylod Timing Buffer |
| RCS | Reaction Control System |
| ROM | Rough Order of Magnitude |
| scc | Standard Cubic Centimeter |
| sec | Second |
| SMCH | Standard Mixed Cargo Harness |
| SOW | Statement Of Work |
| STS | Space Transportation System |
| TCS | Thermal Control System |
| TVS | Thermodynamic Vent System |
| VAB | Vehicle Assembly Building |
| VCS | Vapor Cooled Shield |
| W | Watt |

# I. INTRODUCTION

The Cryogenic Fluid Management Facility (CFMF) is a reusable test bed which is designed to be carried into space in the Shuttle cargo bay to investigate systems and technologies required to efficiently and effectively manage cryogens in space. The facility hardware is configured to provide low-g verification of fluid and thermal models of cryogenic storage and transfer concepts and processes. Significant design data and criteria for future subcritical cryogenic storage and transfer systems will be obtained. Future applications include space-based and ground-based orbit transfer vehicles (OTV), space station life support, attitude control, power and fuel depot supply, resupply tankers, external tank (ET) propellant scavenging, space-based weapon systems and space-based orbit maneuvering vehicles (OMV).

Cryogenic fluid management (CFM) consists of the systems and technologies for: 1) liquid storage and supply, including capillary acquisition/expulsion systems which provide single-phase liquid to the user system, 2) both passive and active thermal control systems, and 3) fluid transfer/resupply systems, including transfer lines and receiver tanks. The facility tankage systems will be configured to investigate methods of integrating pressure control, liquid acquisition and liquid transfer concepts.

The facility design approach includes using liquid hydrogen as the test fluid, designing for seven flights, with current mission planning for three flights, consisting of maximum 7-day test periods as a shuttle-attached payload. The current contracted effort is to carry the detailed design of the facility through a critical design review (CDR), considering potential modifications to the previously defined systems concepts described in NASA CR-165495 and NASA CR-165279. This report documents the Task I trade study and conceptual design effort which will be the basis of the preliminary and detailed CFMF design leading to the CDR in mid 1984.

The Task I Conceptual Definition effort consisted of three subtasks (excluding reporting). The three subtasks and major items addressed in each are listed below, and discussed in greater detail in Chapters II through IV.

- o Cryogenic fluid management technology requirements.
  - Reviewed NASA and DOD mission plans.
  - Categorized and prioritized spacecraft and mission cryogenic fluid management requirements.
  - Assessed state-of-the-art in CFM design relative to requirements, and identified technologies for potential study in the CFMF.
- o Fluid and thermal analysis.
  - Performed a scaling analysis, as appropriate, establishing preliminary definition of CFMF characteristics (size, geometry, etc).
  - Defined unique fluid management system models including assumptions, equations, boundary conditions and methods of solution.
  - Analyzed each unique fluid management system, identifying those areas/assumptions requiring orbital data to resolve.
  - Identified CFMF experimental parameters, including measurement accuracy and frequency.
  - Identification of all portions of analyses and system models to be examined on each mission.

- Establishment of conceptual design.
  - Considered systems described in NASA CR-165279 and NASA CR-165495.
  - Performed CFMF/carrier configuration trades; the candidate carriers included the Spacelab pallet, the Multipurpose Experiment Support Structure (MPESS) and the MDM pallet (which is a mixed cargo carrier version of the Spacelab pallet). A conceptual version of the CFMF on both the Spacelab pallet and MPESS is shown in Figures I-1 and I-2, respectively.
  - Prepared ROM cost and schedule for development and flight of each configuration.

The Task I recommended CFMF Conceptual design resulting from this effort is presented in Chapter V.

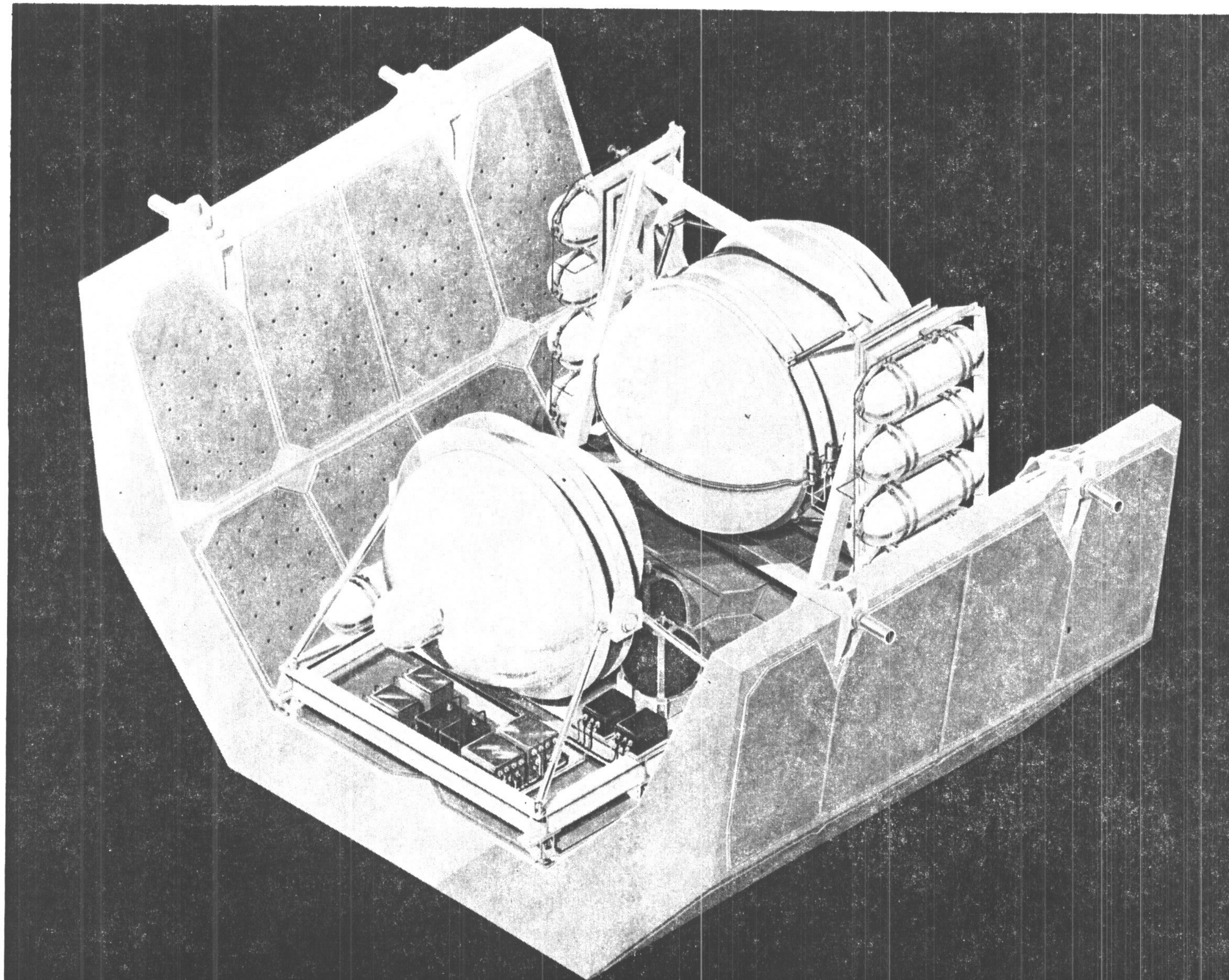


*Figure I-1  CFMF on Spacelab Pallet*

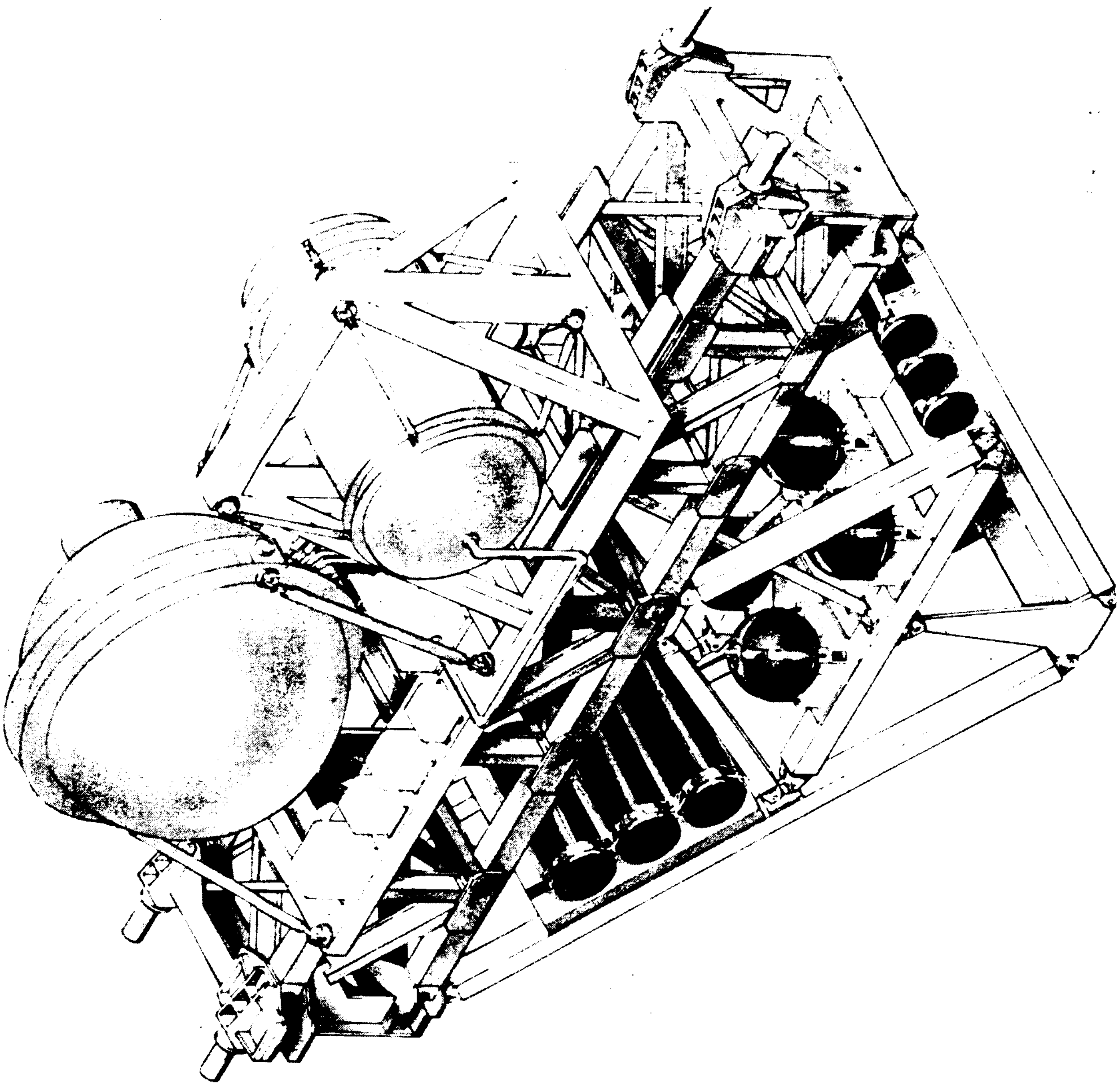


*Figure I-2 CFMF on MPESS Carrier*

# II. CRYOGENIC FLUID MANAGEMENT TECHNOLOGY REQUIREMENTS

NASA and DOD future mission plans were reviewed to identify in-space cryogenic fluid management (CFM) technology requirements. The CFM systems were grouped according to whether they were liquid storage/supply, thermal control or fluid transfer/resupply. Currently planned fluid management systems for each group, comments about state-of-the-art status and suitability for potential study are addressed below. Cryogenic fluid management system elements are illustrated schematically in Figure II-1.

## A. LIQUID STORAGE/SUPPLY SYSTEMS

These systems can be subdivided into three general technology areas, acquisition/expulsion systems, pressurization systems and slosh control systems. Pressurization is most often the energy source for accomplishing the outflow. Some applications require a more positive slosh control of the moving liquid within a tank than is provided by viscous damping along the tank walls.

Acquisition/Expulsion - Expulsion approaches in low-g consist of direct liquid outflow while settled or the use of capillary acquisition devices to capture the liquid for single-phase liquid feed.

1. Direct Tank Outflow with Settling - For main propulsion systems that provide a settling thrust, propellants may be delivered directly from a tank outlet. In particular, several rocket engines operate in a tank head idle mode during a childown phase. This low level operation provides a low thrust level, adequate for propellant settling, and generally, a mixture of liquid and vapor can be accepted by the engine during this period. A concern in the use of this approach is that vapor not reach the engine after the pumps have reached a high speed, since damage may result. Therefore, it is necessary to be able to predict the time required to settle bubble-free liquid to the outlet, and to allow adequate time at low thrust to displace all bubbles that were previously ingested into the line.

Although propellant settling has been employed in space vehicles, better design data and models are needed to reduce conservatism. A liquid settling test could be conducted in the CFMF in which the liquid could be initially settled away from the outlet, giving a known and worst case starting configuration. However, the availability of adequate instrumentation to determine when well-settled liquid is available at the outlet is questionable. Settling of liquid to the outlet to empty the receiver tanks is required, and will be included in the CFMF; quantitative data on fluid quality may not be obtained.

2. Capillary Acquisition Devices - When propellant settling is not practical, other methods must be considered for delivery of single-phase liquid from a tank. Capillary or surface tension forces have proven to be the most useful means for management of fluids in low gravity environments.

Closed capillary liquid acquisition devices make use of the characteristics of fine mesh screen. The tank outlet is connected to various regions of the storage tank by a conduit that may be one or more rectangular channels, or any other configuration that will reach to areas where liquid may be located in low-g. The conduit is made in large part from fine-mesh screen. Because these channels will be in contact with liquid for any low-g orientation, it is called a total communication device. So long as liquid

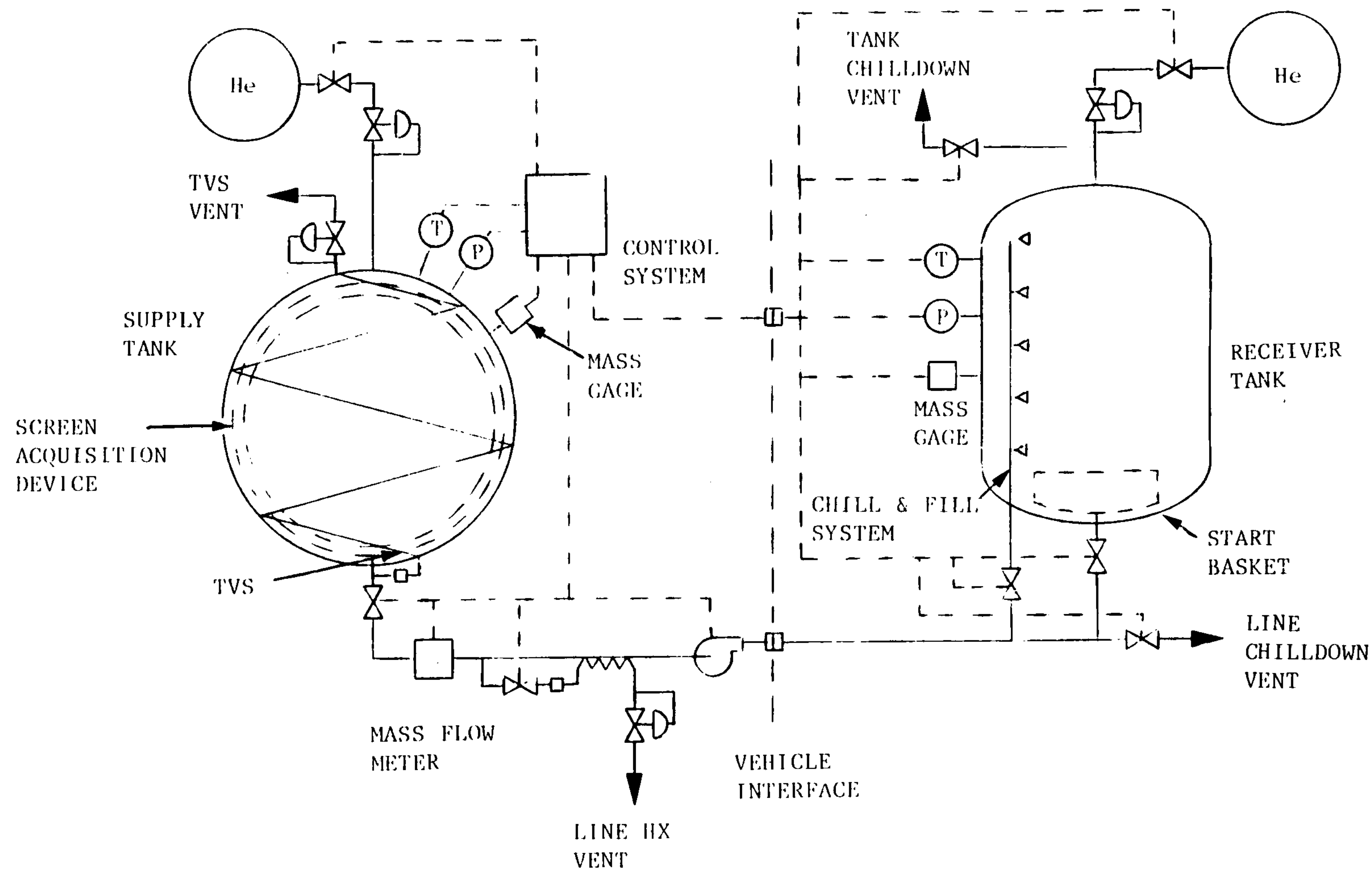



*Figure II-1 Cryogenic Fluid Management Systems Concept Schematic* contacts the screen at any point, liquid will flow into the device during tank outflow, and gas will be blocked out. A closed acquisition system was designed under the Cryogenic Fluid Management Experiment (CFME) program.

When a propulsion system generates a settling thrust, but requires a supply of gas free liquid for start-up, a partial communication acquisition device may be used. This type device is configured as a reservoir located at the tank outlet. The same characteristics of fine-mesh screen act to hold liquid in the device, which is assumed to be initially full, under low-g conditions. If engine start occurs when liquid is oriented away from the outlet region, the reservoir will provide liquid until propellant is settled. Some gas will have entered the device, of course, since the ability of the screen to block gas entry will be overcome when inadequate liquid is in contact with the screen.

Analysis and modeling techniques are well developed for capillary acquisition devices for storable propellants. Systems for cryogenic fluids require the same analyses. In addition, concern must be given to thermal effects, since the cryogens are stored at near their boiling point. It is necessary to provide means for thermal control of closed acquisition devices to prevent vapor formation and displacement of liquid. For this reason, orbital testing of such devices should be a priority objective for the CFMF. In addition to the use of a total acquisition system for the supply tank, a partial acquisition device is recommended to be included in the receiver tank for one mission.

Pressurization - Pressurization must be provided for both supply and receiver tanks to provide for outflow and inerting. Determination of helium requirements is relatively straightforward but is dependant on internal tank thermodynamics in low-g, for which inadequate data exists.

For applications like a space station depot, it would be very desirable to avoid use of non-condensible pressurants, such as helium. Such tanks will be resupplied prior to being completely drained, and a means for removing the pressurant is required in order to avoid over-pressurization during refill. Autogenous pressurization, using heated vapor of the stored liquid, is successfully applied in booster propulsion systems. However, for low-g applications, the thermodynamics are somewhat different. In a boost environment, the high-g field helps to maintain temperature stratification which is required to prevent excessive cooling and condensation of the pressurizing vapor. Current capabilities for analysis of low-g autogenous pressurization are inadequate, and orbital testing of such a system is recommended as a high priority for CFMF.

Slosh Control - Many future space missions, such as telescope platforms and directed beam weapon systems, require extremely close control of vehicle attitude. In low-g very large amplitude liquid motion can result from relatively small disturbances such as attitude change and thrusting for orbit correction. It is anticipated that slosh baffle systems will be required for some of these systems and that the baffle systems could significantly impact other fluid management systems. However, in the absence of specific requirements, it is not appropriate to define and analyze slosh control systems at this time.

## B. THERMAL CONTROL SYSTEMS

Cryogenic storage systems are dependant on effective thermal control for proper performance and reasonable boiloff losses. Systems for thermal control can be categorized under two groups; thermal protection systems are required to minimize heat leak and thermal management systems are required to minimize venting and pressure excursions resulting from the heat leak.

Thermal Protection System - Heat reaches cryogenic tanks through the tank insulation, the support system, the pipes attached to the tank, and any other penetrations such as instrumentation lead wires. Heating rates are also strongly influenced by the thermal environment and provisions that may be incorporated to reduce external heating such as thermal coatings or sun shields. Most of the thermal analysis is straightforward and based on adequate data. An exception is heat transfer through multilayer insulation (MLI). The performance of MLI varies somewhat under laboratory conditions. When applied to actual tanks, however, there is considerable degradation and much greater variation in heat transmission. Discontinuities due to seams and closeouts around penetrations are sources of added heat leak, and variations in layer density influence performance. A particular concern is with larger systems, and particularly if thicker blankets are to be used. For such systems, the weight of the MLI will be much greater than for the tanks that have been insulated and tested to date. Current methods of attaching and supporting the MLI may be inadequate, and self compression, particularly during earth to orbit transport, will be much greater. Size limitations for the CFMF preclude addressing the self compression issue. However, the space performance of insulation blankets of at least 30 layers in thickness should be addressed by CFMF.

Ground loading of liquid hydrogen requires that air not be allowed in contact with the tank to prevent condensation of nitrogen and oxygen. One approach to preventing air contact with the tank is to use a vacuum jacket around the tank; this is the concept recommended for the supply tank which will be loaded on the ground and carry the hydrogen into orbit. The conventional non-vacuum-jacketed approach is to purge MLI with helium. An alternative non-vacuum- jacketed concept is to install a layer of closed-cell foam insulation directly on the tank, apply the MLI over the foam and purge with dry nitrogen. The foam insulation provides enough thermal resistance to prevent condensation of nitrogen, and the combined effects of the foam and the lower thermal conductivity of nitrogen compared to helium greatly reduces ground hold and ascent boiloff losses. The ground performance of the non-vacuum-jacketed insulation systems can be verified by ground tests, and since the CFMF receiver tank is not loaded on the ground, these concepts will not be part of the CFMF objectives. Evaluation of the insulation purge gas evacuation (e.g. helium and/or nitrogen) during ascent, and on-orbit performance of the insulation system is, however, recommended for inclusion in the CFMF.

Thermal Management Systems - Thermal management is accomplished either by direct tank venting while liquid is settled or by using a thermodynamic vent system.

1. Direct Tank Venting with Settling - For short duration storage of cryogens, it is feasible but may not always be practical to provide for tank pressure control by direct tank venting. This approach requires that the liquid be settled to prevent venting of liquid. Because rebound and splashing can result in returning liquid to or near the top of the tank, sufficient settling time must be allowed to damp these motions. If the tank venting rate is relatively high, boiling may occur at points below the liquid surface as the tank pressure is reduced. Because the rate of bubble rise in the low-g settling environment will be very low, this bulk boiling may also result in liquid approaching the vent port.

Venting of non-condensibles from a partially filled tank prior to resupply or topping of the tank with additional liquid will likely be required. Direct tank venting with settling may be the preferred approach, with the vent open just long enough to allow the original ullage vapor, flowing at sonic speed, to escape, leaving most of the original quantity of liquid still within the tank. This type of venting of non-condensibles is recommended for investigation by the CFMF.

2. Thermodynamic Vent System - The preferred approach for management of the effects of heat leak in space storage of cryogens is use of the thermodynamic vent concept. The Thermodynamic Vent System (TVS) avoids the problem of finding vapor in the tank, and instead accepts liquid from a capillary acquisition device. The liquid is throttled to a lower pressure and temperature and partially vaporized, then continues to be vaporized by absorbing heat from the tank system in a heat exchanger. Heat can also be intercepted along the various heat leak paths, further reducing the rate of heat entering the cryogenic storage system. If the system is well optimized, the net vent rate can be reduced to less than half the rate required for direct tank venting. The TVS, in conjunction with a vapor-cooled shield, is recommended for incorporation into the supply tank for CFMF.

Optimization of the TVS is primarily a matter of placement of heat exchangers to best reduce vent rate. An internal or tank heat exchanger (that could be closely thermally attached to the tank) is required to achieve maximum transfer of heat to the vent fluid at the tank temperature level. This is an essential requirement for efficient TVS operation. Additional heat exchangers may be placed within the tank insulation, using a vapor-cooled shield (VCS), or coupled to tank supports, to pipes attached to the tank or to any other sources of heat leak. Placement of these heat exchangers requires balancing the cooling capacity in the vent fluid with the characteristics of the heat leak to achieve minimum net heat conductance to the tank. TVS performance for $LH_2$ systems can also be improved by utilization of the heat sink capacity gained by endothermic conversion of the vented hydrogen from its initial para form to or near its equillibrium para-ortho composition.

3. Refrigeration Systems - For very long term storage of cryogens, long life refrigerators could reduce venting losses by absorbing the majority of the heat input to the fluid storage tank. This approach is the objective of several long range technology programs, but such refrigerators have not yet reached a state of development that would warrant in-space testing on the Shuttle-attached CFMF. In addition, the 7 day mission time of the Shuttle with CFMF attached is too short to test refrigeration. It may be possible to investigate refrigeration systems with CFMF hardware attached to the space station.

## C. FLUID TRANSFER/RESUPPLY

Planned NASA and DOD missions will require resupply of cryogen storage tanks in space. Low-g effects and the inability to readily vent receiver tanks present new problems, and space experiments are required to provide data needed for design of such systems. Supply tank requirements for propellant transfer are similar to those for other low-g fluid supply systems, such as attitude control systems, except that tank size and delivery rates will be much greater.

Transfer Line Childown - Childown of transfer lines for transfer of cryogens is a well established procedure for ground systems. However, the effect of low-g on heat transfer rates and two phase fluid flow could significantly change the nature of line childown. In long one-g transfer lines, serious pressure surging can occur. For space transfer, line lengths will probably be much shorter and the thermal environment may also be more favorable. A complication, however, is that the transfer line will be part of two vehicles, and disconnect fittings will be required to mate them. The disconnects are likely to be fairly massive, may be mounted with strong thermal coupling to the vehicle structure, and thus will significantly affect the transfer line childown process.

Receiver Tank Childown - For tanks that are initially empty and warm, it is necessary to remove a substantial part of the heat stored in the tank wall before fill can proceed. A charge-hold-vent procedure is recommended by most investigators to accomplish tank childown. The tank is initially evacuated by venting to space. A charge of liquid cryogen is admitted to the tank and the inlet and vent valves are kept closed for a hold period. The tank is then vented and the process is repeated as many times as necessary. For at least the initial charge, the liquid will spatter about the tank, much like drops of water in a hot skillet. In the absence of gravity, however, the drops will tend to be propelled throughout the tank rather than collecting in the bottom of the tank. Heat transfer will also occur between vapor and both the tank wall and the liquid.

The time and quantity of fluid required to chill a receiver tank are dependent on these three modes of heat transfer, which are all gravity sensitive. They are also expected to be dependent on the manner of injection of liquid into the tank and on tank size. The quantity of cryogen that must be delivered to orbit to provide for tank childown could range from little or nothing for large tanks to 5-10 percent for small tanks. The receiver tank thermal condition following childown establishes the starting point for the no-vent fill process, and thus an important goal for the CFMF should be to establish procedures, rates and quantities of cryogen required for childown.

Receiver Tank No-Vent Fill - It is desirable to accomplish resupply of cryogenic tanks in space without venting as the transfer proceeds, since establishing an acceleration environment to settle liquid and clear the tank vent port may significantly impact mission plans. So long as the receiver tank is free of non-condensible pressurant gas, fill can be accomplished without venting. Liquid transfer into the tank can be accommodated with only moderate pressure increase and vapor compression. For the most part, vapor is condensed by transfer of heat to the liquid. This process requires limiting external heating and providing for adequate contact between liquid and vapor.

Analysis and ground test results show that the required heat transfer between liquid and vapor can be readily accomplished so long as the vapor volume is a significant fraction of the total tank volume, say one-fourth or more. But as the tank approaches the desired fill level of 95 percent or more, vapor condensation, and consequently fill rate, becomes severely limited by the decreasing interfacial area between liquid and vapor. The no-vent fill process will depend on use of nozzles to increase forced convective heat transfer, and low-g behavior of the agitated fluid will be important. Development of approaches for no-vent fill and characterization of the low-g effects are high priority objectives for CFMF.

## D. CRYOGENIC FLUID MANAGEMENT PRIORITY ASSESSMENT

Once the CFM technology requirements were defined, they were prioritized based upon their pertinence to specific applications. Those representative of the whole range of requirements included space-station, space-based laser, scientific instrument or facility cryo storage, Shuttle enhancements, Aft Cargo Carrier - External Tank scavenging, resupply tankers, space-based OTV (Aeroassist), ground-based OTV (Aeroassist) and orbit maneuvering vehicles.

The categories for priority assessment were:

| Category | Description |
|---|---|
| 1 | Item must be addressed - enabling technology. |
| 2 | Technology must be addressed for efficient design (min weight, min losses, max performance, etc.) |
| 3 | Technology which provides intermediate performance gains. |

The resulting priority assessments for each of the CFM systems, including some of the specific technology issues for each group, are presented in Tables II-1 through II-3. Technologies that had been identified previously by the NASA Cryo Fluid Management R & T Ad Hoc Planning Committee are appropriately indicated.

Since space station and space-based OTV represent applications with near-term design implications that might benefit from the CFMF orbital test data, it was decided to focus the spherical supply tank with total communication device toward the as-yet unspecified space station requirements, and the receiver tanks toward the space-based OTV. The Boeing space-based OTV with Aeroassist (NASA CR-3535) was selected for receiver tank scaling. The OTV configuration is shown in Figure II-2, and the liquid hydrogen tank characteristics are tabulated in Table II-4.

A review of the CFM systems, technologies, applications, requirements and current status, resulted in the recommendations for CFMF study listed in Table II-5. Additional recommended technology items to those previously defined for the CFMF are listed, as well as those newly identified technology items not recommended for incorporation within the three-flight plan. This latter category represents possible technologies for additional 7-day CFMF missions or an extended mission attached to the space station or an unmanned experimental platform.

The use of liquid hydrogen as the test fluid is preferred because it presents the most difficult of the cryogenic fluids to store and transfer, due to its much lower surface tension (with the exception of liquid helium, which has an order of magnitude lower surface tension than hydrogen and has special handling problems because of its many different physical states). Obtaining low-g storage, resupply and thermal management data for hydrogen will therefore have general applicability to other cryogenic fluids with the exception of liquid helium.

*Table II-1 Liquid Storage/Supply Fluid Management Systems, Technology Issues and Priority Assessment*

| | | Priority Assessment |
|---|---|---|
| ● Fluid Management Systems | | |
| Acquisition/Expulsion Systems | | |
| Direct Outflow with Settling | ● | 2 |
| Total Communication Device | ● | 1 |
| Partial Communication Device | ● | 2 |
| Pressurization Systems | | |
| Ambient Helium | ● | 2 |
| Cryo-cooled Helium | ● | 3 |
| Autogenous | ● | 1 |
| Slosh Control Systems | | 2 |
| ● Additional Technology Issues | | |
| Start Transients | ● | 2 |
| Outage/Pullthrough | ● | 3 |
| Mass Gaging/Instrumentation | ● | 1 |
| Non-conventional Tankage | | 2 |

● Identified previously by NASA Cryo Fluid Management R&T Ad Hoc Planning Committee

*Table II-2 Thermal Control Systems, Technology Issues and Priority Assessment*

| | | Priority Assessment |
|---|---|---|
| ● Thermal Protection Systems | | |
| Vacuum Jacket/Insulation (Dewar) | ● | 3 |
| Purged - MLI | ● | 2 |
| Foam - MLI | | 2 |
| ● Thermal Management Systems | | |
| Thermodynamic Vent Systems | | |
| - Internal Heat Exchanger | ● | 1 |
| - External Heat Exchanger (including vapor-cooled shield) | ● | 1 |
| - Coupled Heat Exchanger (vent free storage) | | 2 |
| - Para-to-ortho conversion | | 2 |
| Direct Tank Venting with Settling | | 3 |
| Refrigeration Systems | | 2 |
| ● Additional Technology Issues | | |
| Insulation Reusability (Non-Dewar) | ● | 2 |
| Insulation Degradation (with time) | | 1 |
| Supports/Lines/Penetration Heat Leaks | | 3 |
| Thermal Acoustic Oscillations | ● | 3 |
| Convection Control | ● | 3 |
| Thermal Conditioning Outflow | | 1 |

● Identified previously by NASA Cryo Fluid Management R&T Ad Hoc Planning Committee

*Table II-3 Fluid Transfer/Resupply Technologies and Priority Assessment*

| | | Priority Assessment |
|---|---|---|
| ● Receiver Tank | | |
| Empty | | |
| Childown | ● | 1 |
| Acquisition Device Fill | ● | 1 |
| Vapor Collapse | ● | 1 |
| Purge, Non-Condensibles | ● | 1 |
| No-vent Fill | ● | 1 |
| Partially Full | | |
| Venting Non-Condensibles | ● | 1 |
| No-vent Fill | ● | 1 |
| Vented Fill | ● | 2 |
| ● Transfer Line | | |
| Childown | ● | 1 |
| Quick Disconnect | | 1 |
| ● Additional Technology Issues | | |
| Mass Gaging | ● | 1 |
| Mass/Quality Metering | ● | 1 |
| Pump vs. Pressurized Transfer | | 2 |
| Long Term Effects | | |
| Repeated Cycling Degradation | | 3 |
| Contamination | | 3 |

● Identified previously by NASA Cryo Fluid Management R&T Ad Hoc Planning Committee

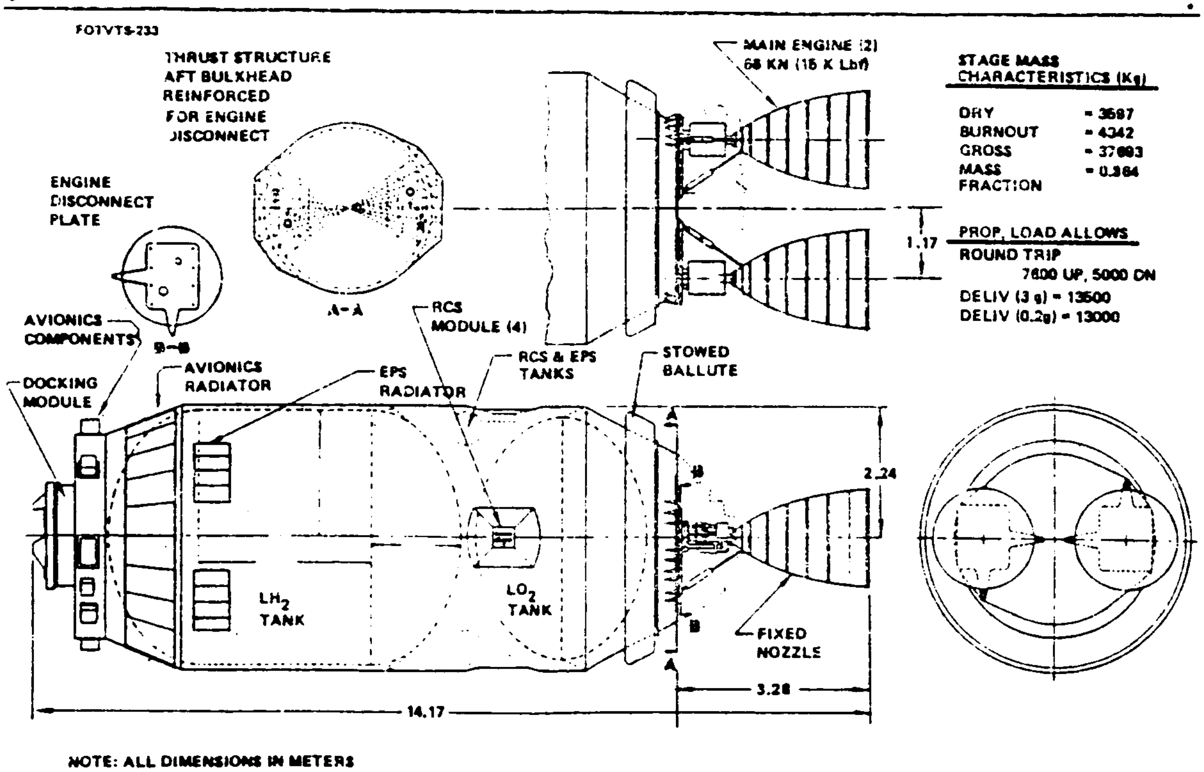



*Figure II-2 Space-based Orbit Transfer Vehicle Configuration (Ref. NASA CR 3536)*

*Table II-4 Spaced Based OTV - $LH_2$ Tank Characteristics*

| | | | |
|---|---|---|---|
| • Tank Configuration: | | | |
| | Geometry | Cylindrical with Elliptical Domes | |
| | Volume | 71.58 $m^3$ | (2528 $ft^3$) |
| | Diameter | 4.28 m | (14.08 ft) |
| | Total Length | 5.97 m | (19.57 ft) |
| | Surface Area | 86.41 $m^2$ | (930 $ft^2$) |
| | Thickness | 0.065 cm | (0.025 in) |
| | Material | 2219-T87 Aluminum | |
| • Tank Weights: | | | |
| | Dry Tank | 354 kg | (780 lbm) |
| | Loaded Fluid ($LH_2$) | 4658 kg | (10250 lbm) |

*Table II-5 Technology Recommendations for CFMF*

- Additional recommended technology items for CFMF (to those previously defined in NASA CR-165495 and NASA CR-165279)
  - Autogenous pressurization/supply tank
  - Foam-MLI on receiver tank
  - Transfer line thermally-simulated disconnect

- Technologies not recommended for incorporation into CFMF.
  - Coupled TVS*
  - Refrigeration systems*
  - Slosh control (needs further assessment)
  - Unconventional tankage
  - Liquid helium fluid management in low-g
  - Long term storage effects (e.g. insulation degradation)*
  - Para-to-ortho conversion* (needs further assessment)
  - Detachable supports*

* Possible technologies for investigation on an extended (6-month) CFMF experiment where the facility is removed from the cargo bay and attached to the space station or an unmanned experimental platform.

# III. FLUID AND THERMAL ANALYSIS

The cryogenic fluid management systems, technologies and technical issues that were identified in Chapter II as requirements for future NASA and DOD space missions were analyzed and evaluated to support the CFMF concept definition. Each fluid management system was evaluated to identify the underlying principles and to determine whether orbital data is required to develop analytical models for future system designs. Scaling relationships were examined to assess the applicability of the CFMF as a test bed for obtaining required data for the fluid management systems. Analysis and modeling of the systems determined experiment requirements, experiment size constraints, parameters of interest and instrumentation needs. These results, along with the identified technology issues and requirements, were used to establish CFMF objectives and recommended configurations and timelines for a three mission experimental program.

## A. SCALING ANALYSIS AND MODELING APPROACH

Scaling analyses were performed for the various fluid management systems to provide guidance in sizing the CFMF and to help assess the adequacy of modeling and analysis approaches. The scaling analysis involved examining the dimensionless parameters, such as Reynolds number, Bond number, Grashoff number, etc., that are important to the various fluid management systems being investigated. Equations, basic principles and available data that apply to the individual systems were also determined. These relationships and data were evaluated to determine how test data can be related to the design of the full scale model, to assess the validity of the data, and to determine the criteria that must be observed in design of the scale model experiments to assure that the resulting test data can be correctly evaluated and applied to future spacecraft cryogenic systems.

Many, if not all, important processes can be characterized in terms of dimensionless parameters and relationships. Where the process or phenomenon can be isolated from interaction with other processes, data can usually be obtained from experiments in which these dimensionless parameters and relationships can be directly determined. When all of the dimensionless groups that are important to the phenomenon can be kept constant between the experiment and the prototype for which the data is to be used, then the results can be applied directly. Generally, geometric relationships, which are dimensionless ratios of dimensions, are held constant for experiments that are designed to characterize a particular system design. When linear dimensions such as length or diameter enter into the other important dimensionless groups, then the ability to conduct experiments with reduced scale models is limited. In some cases, other physical characteristics of the experiment, such as fluid properties, can be varied to compensate for the reduced dimension. Where several of the important groups have different dependencies on the model dimension, it may be impossible to vary other parameters so as to preserve the value of all of these groups between the prototype and the reduced scale model. There may also be incompatibilities that result from combining more than one process or phenomena in the same experiment, thereby increasing the number of dimensionless groups that need to be controlled.

Some phenomena have specific regimes of behavior. Fluid flow and convective heat transfer have distinct laminar and turbulent regimes. It has been well established that the fluid flow regime is characterized by the value of the Reynolds number, when properly defined for the type of situation. Convective heat transfer is similarly characterized as being in the laminar or turbulent regime by the value of the Reynolds number or the Grashoff number for forced and free convection, respectively. It is usually possible to extrapolate test data for which the values of the dimensionless groups of importance are different between test model and prototype on the basis of known performance of similar systems. However, it is necessary that the behavior regimes for the various processes be the same between the two for the test data to have any validity. Figure III-1 illustrates that the Reynolds number can be maintained in the turbulent regime for mixing or forced convection within a tank over a wide range of model tank sizes.

A means for overcoming the limitations of direct application of the test data is the use of appropriate modeling techniques. Mathematical models, in theory, simultaneously solve all of the significant equations that describe the behavior of a system. In practice, it is some of these equations that are being determined by the experiment. However, by incorporating the known equations and the best available estimate of the unknown relationships, a model can be used to predict the results of the experiments. By comparison of predictions against results, the discrepancies can be identified and the presumed relationships can be modified to improve the correlations. When a sufficient quantity and variety of test data has been satisfactorily correlated, the model can predict performance for other systems and can be

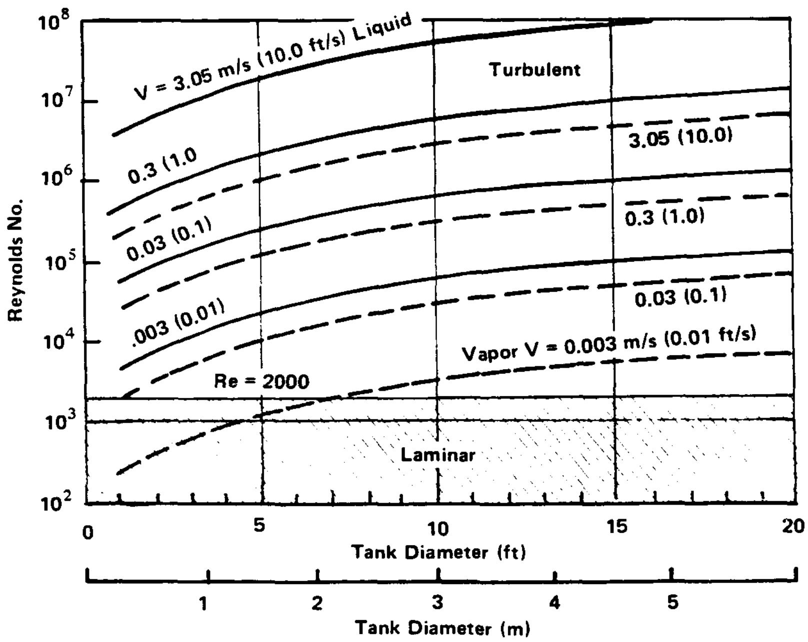



*Figure III-1 Reynolds Number vs Tank Size and Fluid Velocity for Hydrogen* used in design of the prototype systems. The Martin Marietta developed Cryogenic Systems Analysis Model (CSAM) is being used in the CFMF program in this manner. This comprehensive computer code is useful in modeling many of the fluid management systems being investigated, including receiver tank chilldown and no-vent fill during fluid transfer, transfer line chilldown, pressurization system performance, direct venting and low-g venting using the thermodynamic vent system for longer term storage. It models heat transfer and the thermodynamics of the fluids, and incorporates an extensive data base of properties of a number of cryogenic fluids. CSAM also is capable of simulating a variety of mission event sequences that can be specified as input data.

## B. ANALYSIS OF FLUID MANAGEMENT SYSTEMS

Presented here are the analyses which were performed for the major fluid management systems to determine expected performance, to evaluate the need for orbital data and to support the conceptual design of the fluid management facility. The scope of the analyses included reviews of previous work, manual calculations, and modeling and simulation using the CSAM program and other computer models, as appropriate. A complete fluid and thermal analysis report covering analysis of all unique fluid management systems will be published following completion of the detailed design. Some of the pertinent observations, conclusions and recommendations are discussed below.

Receiver Tank Chilldown Transfer of cryogens from one tank to another in space for resupply or for initial tanking of tanks boosted to space empty will be one of the critical areas for which technology must be developed. When the tank to which the cryogen is transferred is initially empty and warm, the first step in the process will be to cool that tank down to an acceptable temperature for the transfer to begin. A widely accepted concept for receiver tank chilldown is the charge-hold-vent approach. A quantity of liquid cryogen is admitted to the warm tank that is initially evacuated. This charge is held in the tank for a sufficient time for transfer of heat from the tank to the fluid. The liquid is vaporized and the warm vapor is vented to space. This process may be repeated as necessary, depending on the initial temperature and mass of the tank.

The temperature to which the tank must be chilled is dependent on the no-vent fill process that is to follow. If the transfer is started with the receiver tank at too high a temperature, the final pressure will be excessive. The final temperature of the transferred liquid will also be increased, and this will result in a lower density and a reduction in the quantity of liquid transferred. Figures III-2 and III-3 show the relation of tank temperature and mass-to-volume ratio on the final conditions at the end of transfer. The required chilldown temperature is a function of the tank mass-to volume ratio, since it is the tank mass that stores the excess heat. For very lightweight spacecraft tanks, little if any chilldown may be required. For small scale experimental tanks, there are problems in achieving such low ratios of tank mass to volume. These include minimum gages of material for manufacturing, but more importantly, higher safety factors and other conservatisms are necessary to avoid prohibitive costs. For the CFMF, it is estimated that the tank mass-to-volume ratio will range from 24.0 to 37.3 $kg/m^3$ (1.7 to 2.33 $lb_m$ per cu-ft), and chilldown to a temperature of 55.6°K (100°R) or less will be required.

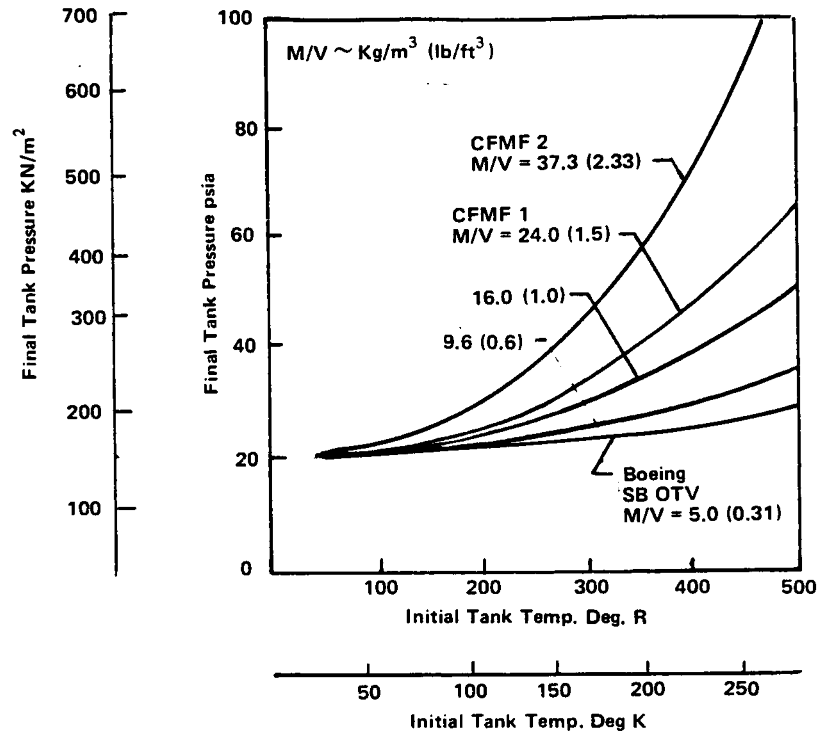



*Figure III-2 Final Pressure after No-Vent Fill vs Initial Temperature*

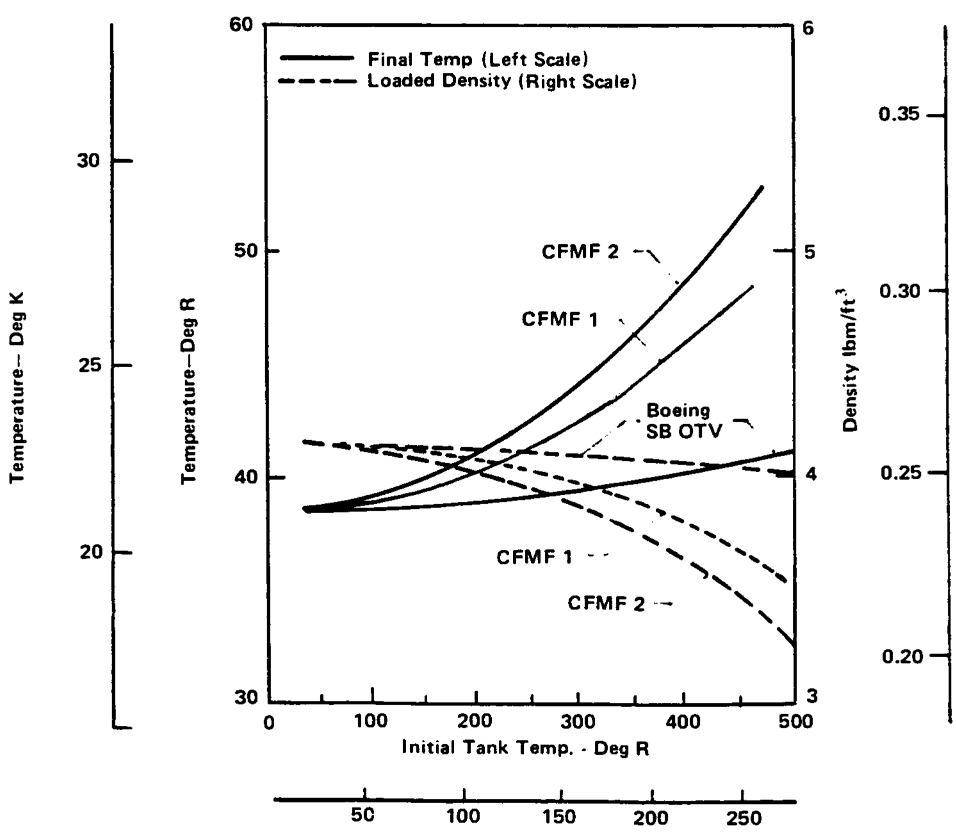



*Figure III-3 Final Temperature and Fluid Density after No-Vent Fill vs Initial Temperature*

Figure III-4 shows CSAM results of a prechill charge/hold simulation for a full-scale, a 0.5, 0.2 and 0.1-scale Boeing Space-Based OTV liquid hydrogen tank. The wall thickness was varied for these tanks to hold the mass-to-volume ratio equal to 5.0 kg/m$^3$ (0.31 $lb_m$/cu-ft), that predicted for the full scale OTV. The ratio of mass of the liquid hydrogen charge to the tank volume was also held constant at 0.8 kg/m$^3$ (0.05 $lb_m$ per cu-ft). The initial tank wall temperature was 278°K (500°R) and the liquid hydrogen charge was saturated at 138 kN/m$^2$ (20 psia). The tanks were all assumed to have 23 layers of MLI. The smaller tank reaches a minimum temperature much sooner than the larger tank as a result of expected differences in heat transfer and the fact that the ratio of tank area-to-mass is greater for the smaller tank. The effect of heat transfer during the process can be noted in that the smaller tank begins to warm after reaching its minimum temperature.

The receiver tank childown experiment is an example of the difficulty or inability to maintain the same value for the dimensionless groups or parameters between the experiment and full size tanks. In particular, the tank mass-to-volume ratio has been identified as one of the important parameters for this process. Figure III-4 shows that even when this ratio is held constant, there is a significant variation in childown characteristics for different tank sizes. For the CFMF, this parameter varies by nearly an order of magnitude between the expected experiment size and the identified prototype vehicle. However, accounting for the different tank heat capacities is relatively straightforward, and the more important information to be gained from the CFMF tank childown experiment is the characterization of the heat transfer processes.

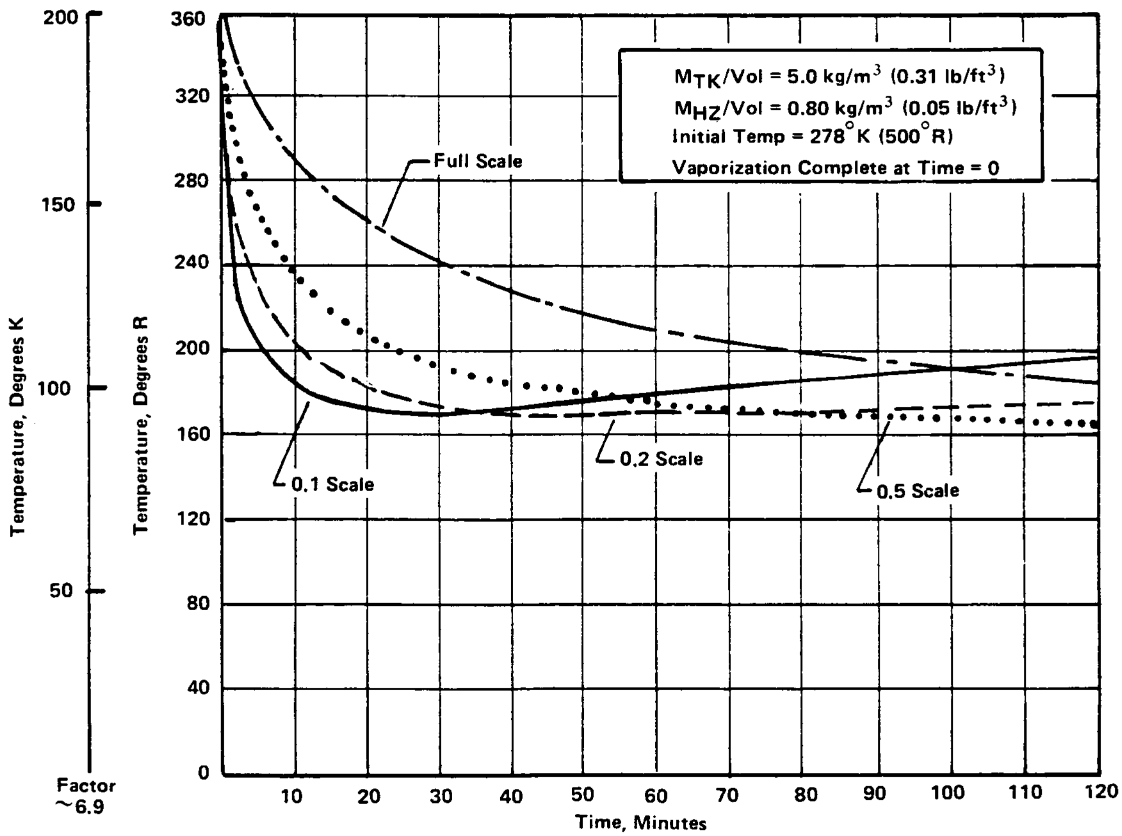



*Figure III-4 Simulation of Tank Childown*

Heat transfer will occur by three major modes. Initially, the liquid will partially vaporize as it comes into equilibrium with the reduced pressure in the tank. The remaining liquid will tend to break into drops and to spatter against the hot tank wall, being repelled by the vaporization that occurs during the brief period of contact. The vapor generated by the initial flashing of the liquid and by subsequent vaporization will exchange heat with the wall by free or forced convection or by conduction. Finally, the drops of liquid moving through the tank will absorb heat from the vapor and will tend to vaporize as a result. These heat transfer processes will be governed by the fluid properties, the tank wall and fluid temperatures and the tank size. It is possible by proper modeling to account for the discrepancy in tank mass-to-volume ratio to a much greater extent than it is to determine the heat transfer characteristics by ground testing or evaluation of available data.

Because tank size is expected to be an important variable, it is recommended that two tank sizes be used in investigating tank childown. The greater mass-to-volume ratio expected for the experiment tanks provides two benefits. In theory, less quantity of cryogen will be required if multiple charge cycles are employed. This is illustrated in Figure III-5 and III-6. If a smaller quantity of liquid is admitted, the tank temperature reduction will be less on the first cycle, and the vapor that is vented at the end of the cycle will be at a higher temperature. It will therefore have gained more heat. Subsequent cycles will similarly discharge warmer vapor, except for the last cycle. For a single charge cycle, the vapor must be vented at below the required final tank temperature, and it therefore will not have gained as much heat as in the multiple charge case. For the greater tank mass-to-volume ratio, it is necessary, as well as desirable, to perform multiple charge cycles. The second advantage comes from the fact that the multiple charge cycle experiment will evaluate heat transfer repeatedly; each cycle with a different tank wall temperature. This will provide more heat transfer data and the data will be more readily interpreted since the tank wall temperature will vary less during each cycle.

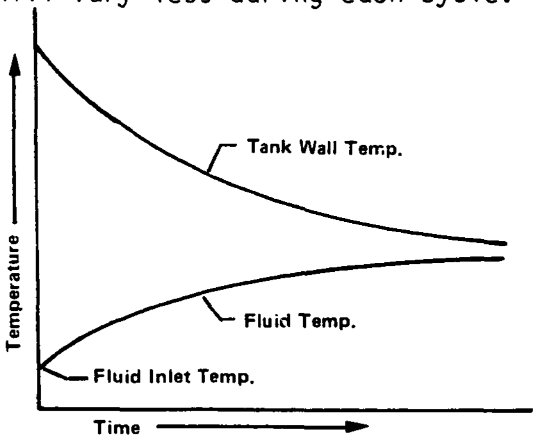



*Figure III-5 Single Charge Cycle*

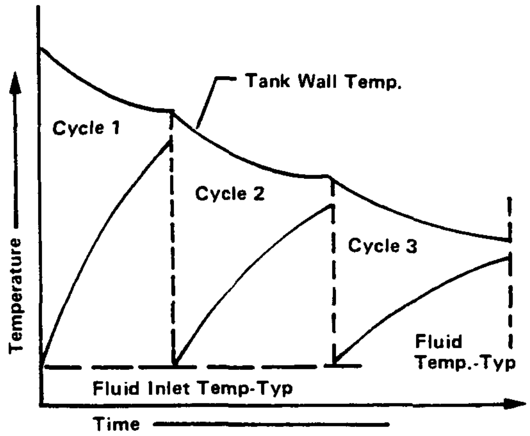



*Figure III-6 Three Charge Cycles*

<u>No-Vent Fill of Receiver Tank</u> - Because of the difficulty of directly venting gas from a tank in a low-g environment, the no-vent fill concept is the most promising approach for transfer of cryogens in space. Analysis shows that the thermodynamic processes in the receiver tank are somewhat involved, and that adequate data for prediction of rates at which the transfer can be accomplished are not available.

Analysis of the thermodynamics in the receiver tank during transfer can be considered in three phases. The first phase, starting at the beginning of transfer, involves vaporization of part of the incoming liquid, or flashing. This occurs because the pressure in the tank is lower than the vapor pressure of the incoming liquid, and it partially vaporizes. During this phase, additional vaporization may occur due to excess heat contained in the tank walls and internal hardware, if they have not been prechilled to liquid temperature.

Flashing of the liquid continues until the incoming liquid is in equilibrium with the tank pressure. At that point, the second phase begins. Continued inflow of liquid causes compression of the vapor, and the tank pressure will rise above the vapor pressure of the incoming liquid. As the pressure increases, vapor will begin to condense at the liquid interface, the third phase of the process. When the receiver tank pressure reaches its maximum operating limit, further transfer into the tank can occur only as condensation of vapor makes room for more liquid.

Condensation of the vapor is the most important process in the no-vent fill procedure, and the liquid-vapor interface area available for condensation as well as the liquid-vapor rate at which condensation occurs will limit the rate at which transfer can proceed. Whenever the liquid interface is at a temperature that is below the saturation temperature corresponding to the tank pressure, vapor will condense at the interface. However, this condensation deposits the heat of condensation into the interface layer, and quickly raises its temperature to the saturation point. Further condensation is dependent on transfer of heat from the interface into the bulk of the liquid. To enhance this heat transfer, means for promoting mixing should be provided.

The mechanism of mixing within the liquid for one-g processes and the prediction of condensation rates is dependent on the liquid-vapor interface being positioned by gravity in a minimum area configuration. In low-g, however, the interface configuration is established by surface tension forces and the interface position will be influenced by the flow of liquid into the tank. In addition, under low-g conditions, the interface area is expected to be increased with effective mixing by the generation of vapor bubbles within the liquid which may not separate due to the lack of buoyancy. Consequently, the effectiveness of mixing methods are expected to be less predictable than would be anticipated for earth-based experiments and the prediction of condensation rates will be more difficult.

As the quantity of liquid transferred increases, the volume of the vapor decreases, and as the tank approaches a nearly full condition the total interfacial area, regardless of the mixing mode, decreases. Therefore, it is possible that the rate of transfer will be severely limited as the tank becomes filled to the 80 or 90 per-cent level. It is also important to note that the ratio of the interfacial area, for any given fill level and geometric liquid-gas configuration, to the volume of the tank, decreases as the tank size increases. This suggests that the fill rate will be dependent on the interfacial area, not the tank volume, and that a large tank will require a longer time to fill than a similar smaller tank.

The no-vent fill process has been analyzed, using the CSAM computer program. Factors describing the heat transfer processes and the interfacial area, that are dependent on the mixing mode and energy, have been varied parametrically. These simulations support the conclusions presented above, and indicate that transfer times will be one hour or more for larger tanks, based on assumptions that are judged to be optimistic. Figure III-7 presents the pressure and percent full versus time for a typical no-vent fill simulation.

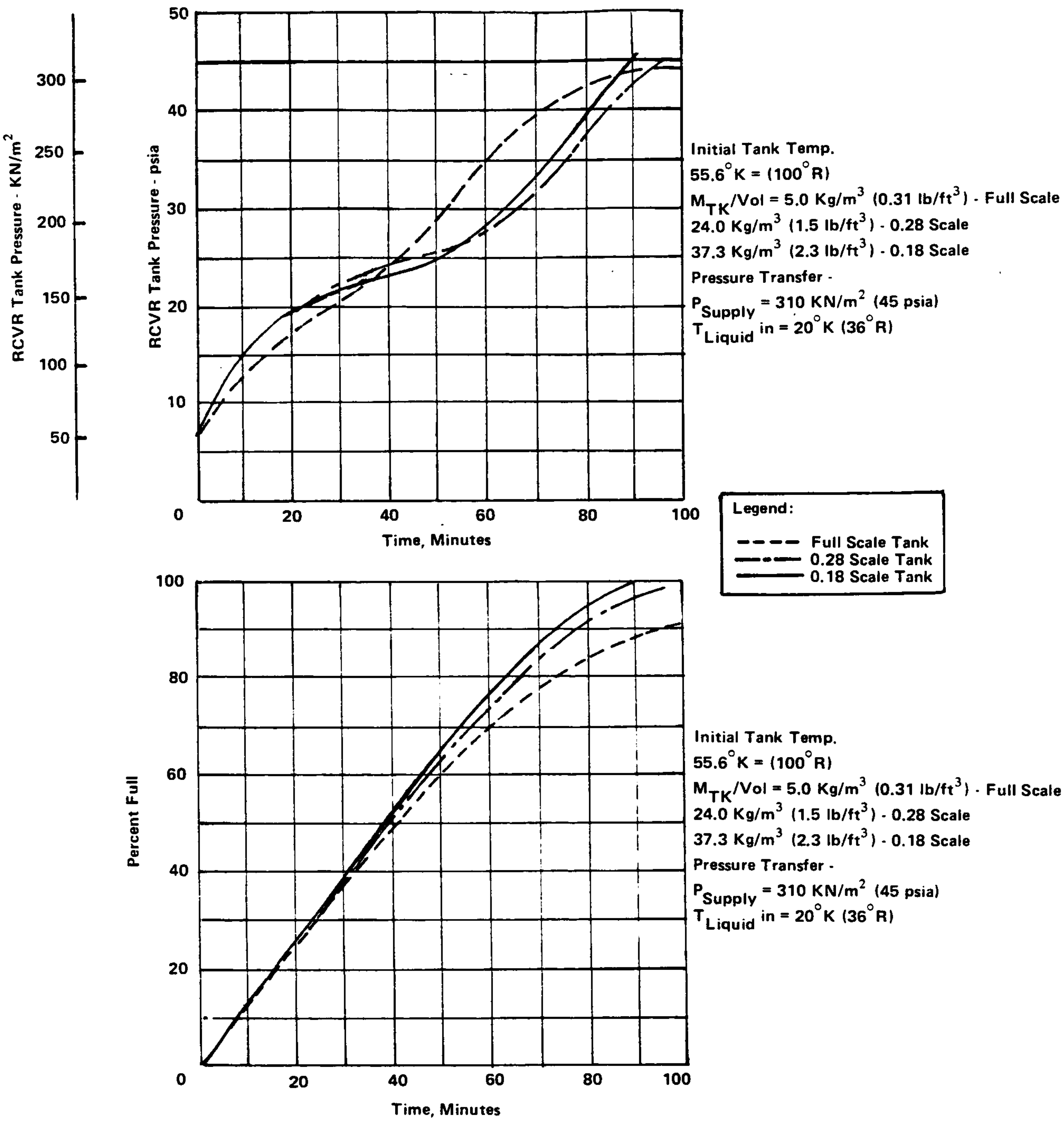



*Figure III-7 Pressure and Percent Full vs Time for Typical No-Vent Fill Simulation*

The need for data on the no-vent fill process in space is critical, and it is proposed that no-vent fill experiments be included in the CFMF. Because it is desirable to evaluate mixing modes, two nozzle configurations are recommended, using the transfer flow as the source of mixing energy. A set of tangential nozzles will extablish a rotational motion of the fluid within the tank, giving an ordered and known liquid-vapor interfacial configuration. A second set of nozzles will be oriented axially, establishing a second flow pattern within the tank. These axial nozzles, when used in conjunction with the tangential nozzles, will tend to give a more random motion of the liquid. By comparing the rates of fill, these mixing modes can be characterized. Because the transfer rate is expected to decrease as the tank fills, it is important that sufficient quantity of liquid be available to completely fill the tank so that this effect can be characterized.

Tank Pressurization - The primary concerns in analysis of tank pressurization systems is to determine the possible effects of the space environment on performance and to evaluate autogenous pressurization as a means to eliminate the need for a non-condensible pressurant.

In a typical system using a non-condensible pressurant such as helium, the helium will be stored at the ambient temperature of the spacecraft (although it may be stored cryogenically to reduce volume requirements). When the warm pressurant is injected into the cryogen tank to maintain pressure during outflow, its density will be small and less pressurant will be required. As the outflow proceeds, the pressurant in the tank will cool, increasing its density with a resulting tendency to reduce tank pressure. At the same time, vaporization of the cryogen will occur to bring the partial pressure of the stored fluid into equilibrium with the liquid. This has the effect of increasing tank pressure. Whether the pressure increases or decreases after the outflow is completed is dependent on various parameters, including the inlet temperature of the pressurant, the liquid outflow rate, the size of tank and quantity of liquid remaining, and both the internal and external heat transfer characteristics. The heat transfer that governs both cooling of the ullage and mass transfer due to vaporization will be affected by the low gravity environment. This is due both to the difference in free convection, and also the liquid-gas configuration that may exist, including liquid motions that may persist after outflow is complete.

An autogenous pressurization system uses heated vapor of the stored cryogen as the pressurant. It will cool down after (as well as during) outflow. Vaporization or condensation may occur, depending on the same parameters that affected the heat and mass transfer when a non-condensible pressurant is used. Autogenous pressurization always results in an input of heat into the tank, and may result in an increased liquid temperature, and/or additional venting to maintain tank pressure during coast periods.

Figure III-8 provides a comparison of the two pressurization methods for a CFMF supply tank for a 40 minute outflow at 27.3 kg (60 $lb_m$) per hour following a 24 hour hold period. For the helium pressurant case, the pressure drops rapidly at the end of outflow and pressurization, due to cooling of the pressurant which was not well mixed during injection. After reaching a minimum, the pressure begins to increase due to vaporization of hydrogen. Two cases are shown for the autogenous system. In the first, the hot hydrogen pressurant was not well mixed. A rapid drop in pressure occurred due to cooling of the vapor, but this was followed with a small pressure rise due to vaporization due to the added heat. The second autogenous case assumed mixing of the

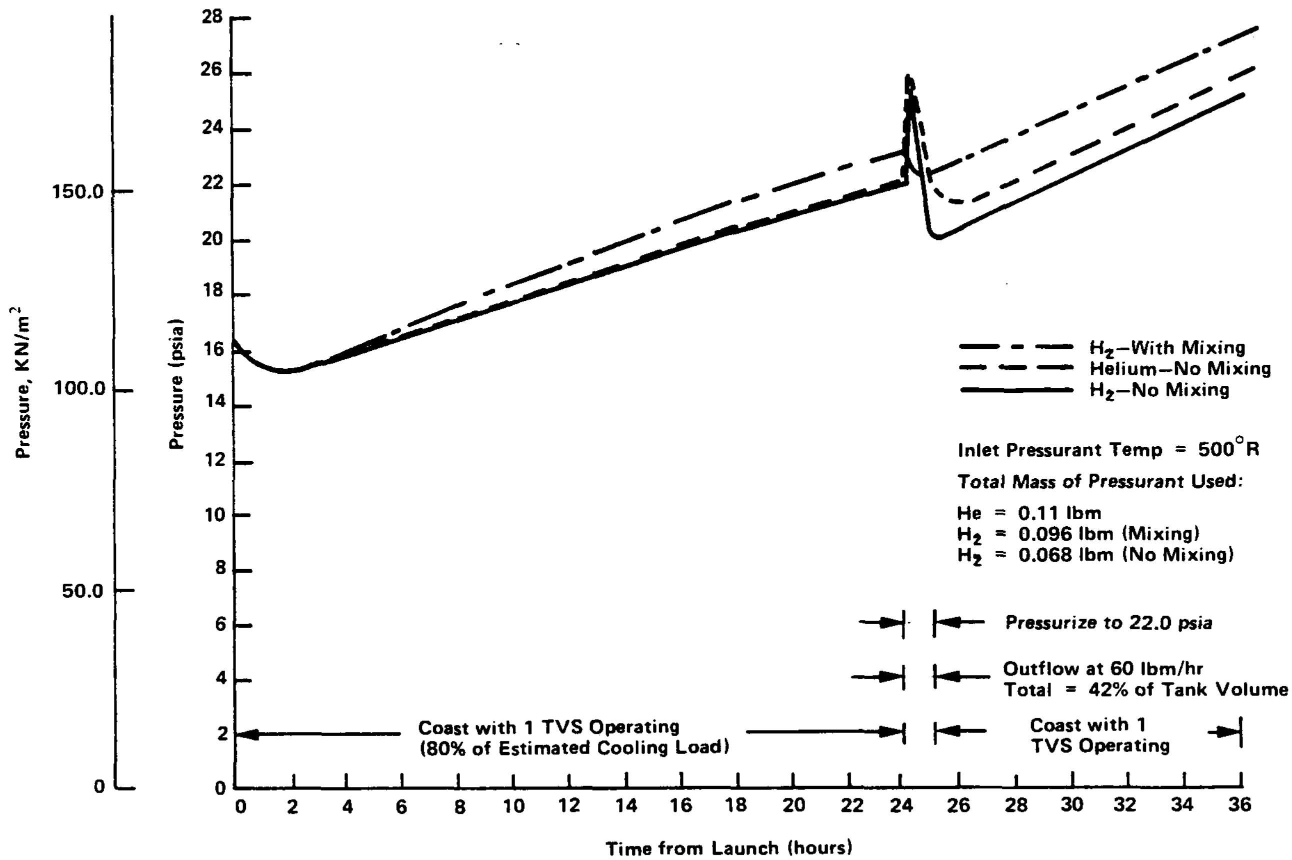



*Figure III-8 CFMF Supply Tank Pressurization Comparison*

incoming hydrogen pressurant. This resulted in a significant increase in the quantity of pressurant required, but with less collapse after the outflow was complete. In all cases, the final rate of pressure rise is due primarily to the heat input to the tank via insulation, supports and piping.

It is recommended that both the non-condensible and autogenous pressurization modes be included in the CFMF in order to characterize the space effects on each. By correlating tank pressure, pressurant quantities and mission events that give insight into the propellant behavior, the heat and mass transfer characteristics can be established.

Space Storage of Cryogens - Because heat leaks will normally be present with cryogenic storage systems in space, means must be provided for accomodating the accumulation of heat in the fluids. The type of system that will be needed will depend on the size, heat leak characteristics and mission duration.

For very short missions, provision for a moderate increase in tank pressure may eliminate the need for venting. The accumulated heat in the fluid will result in an increase in temperature and therefore tank pressure. However, for a minimum increase in pressure it is necessary to minimize stratification of the temperature within the fluid. This can be accomplished with some means for mixing, such as an electrically driven pump-nozzle or fan arrangement. As an example, a 28.3 $m^3$ (1000 cu-ft) spherical hydrogen tank with an average heat leak of 3.15 $w/m^2$ (1 BTU/sq-ft-hr) would increase from 138 to 207 $kN/m^2$ (20 to 30 psia) in about 60 hours if the fluid is maintained at a uniform temperature. An average heat input of 10 watts due to the mixer was assumed.

For intermediate term storage, some means of venting will be required. It may be possible to settle the liquid, using a propulsion system, and to directly vent vapor. A problem with this method is that vaporization will occur within the bulk of the liquid as the pressure is reduced, and the venting rate will be limited by the rate at which the vapor bubbles can rise through the liquid. If the tank is vented too fast, depending on the settling acceleration, the liquid volume will swell due to the vapor generation and liquid will reach the outlet.

For longer term storage of cryogens in space, the thermodynamic vent system (TVS) concept is most appropriate. This method relies on admitting liquid into the vent system, where its pressure is reduced. The vent fluid is routed through a heat exchanger where it vaporizes by absorbing heat from the tank and fluid, and pressure rise is reduced or eliminated. Because of the thermodynamic characteristics of the cryogen, an advantage is gained over direct venting, on the order of 5 to 10 percent. However, if the system is further optimized by routing the vent fluid through additional heat exchangers to intercept heat in the major heat leak components, such as insulation and piping, the total vent rate can be reduced to 50 percent or less when compared to direct venting.

When the thermodynamic vent system is used, it is still necessary to limit the temperature stratification within the fluid to prevent excessive pressure excursions. One approach is to use a pump or fan system to mix the fluid. This has the disadvantage for long term storage that the mixer adds heat to the cryogen. A promising approach to control of stratification that eliminates the need for a mixer is to configure the thermodynamic vent system with two or more heat exchangers. Each is separately routed to remove heat from different sections of the tank, and each is separately controlled to divide the total cooling capacity among the various regions so as to limit temperature differences. Simulations of such systems using the CSAM computer program have verified the feasibility of accomplishing stratification control in this manner without significant reduction of the vent efficiency. Thermodynamic vent systems are proposed for the CFMF supply tank and for the mission two and mission three receiver tanks. In the case of mission three, a separate TVS heat exchanger will be installed on a partial liquid acquisition device for thermal control. The acquisition device will also be configured for passive thermal control, using capillary pumping of liquid to prevent excess heating. The two methods will be compared by operation with and without activation of the TVS heat exchanger.

Partial Acquisition Device - An analysis was made of a refillable acquisition device design for the receiver tank, and a preliminary design concept is shown in Figure III-9. The trap volume is about 6 percent of the total tank and consists of a vent tube and an internal capillary channel device. The bottom portion of the trap consists of 165 x 800 mesh screen. The top portion of the vent tube is perforated with holes 0.13 cm (0.05 in.) in diameter to allow purging of the entrapped vapor during refill.

An analysis was conducted to determine the refill time using the OMS engines to provide a settling acceleration on the order of 0.05 g, and the fill level as a function of time is shown in Figure III-10. This analysis was performed using the REFILL computer program. This program simulates acquisition device performance by evaluating pressure differences due to

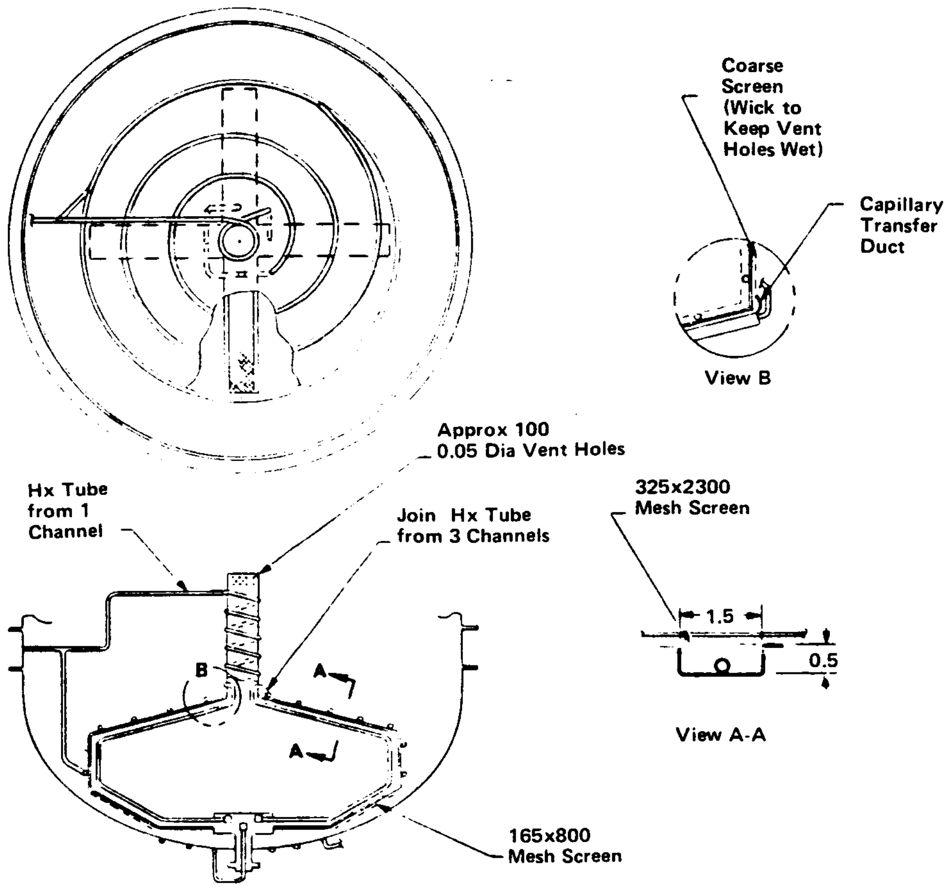



*Figure III-9 Refillable Partial Acquisition Device Concept*

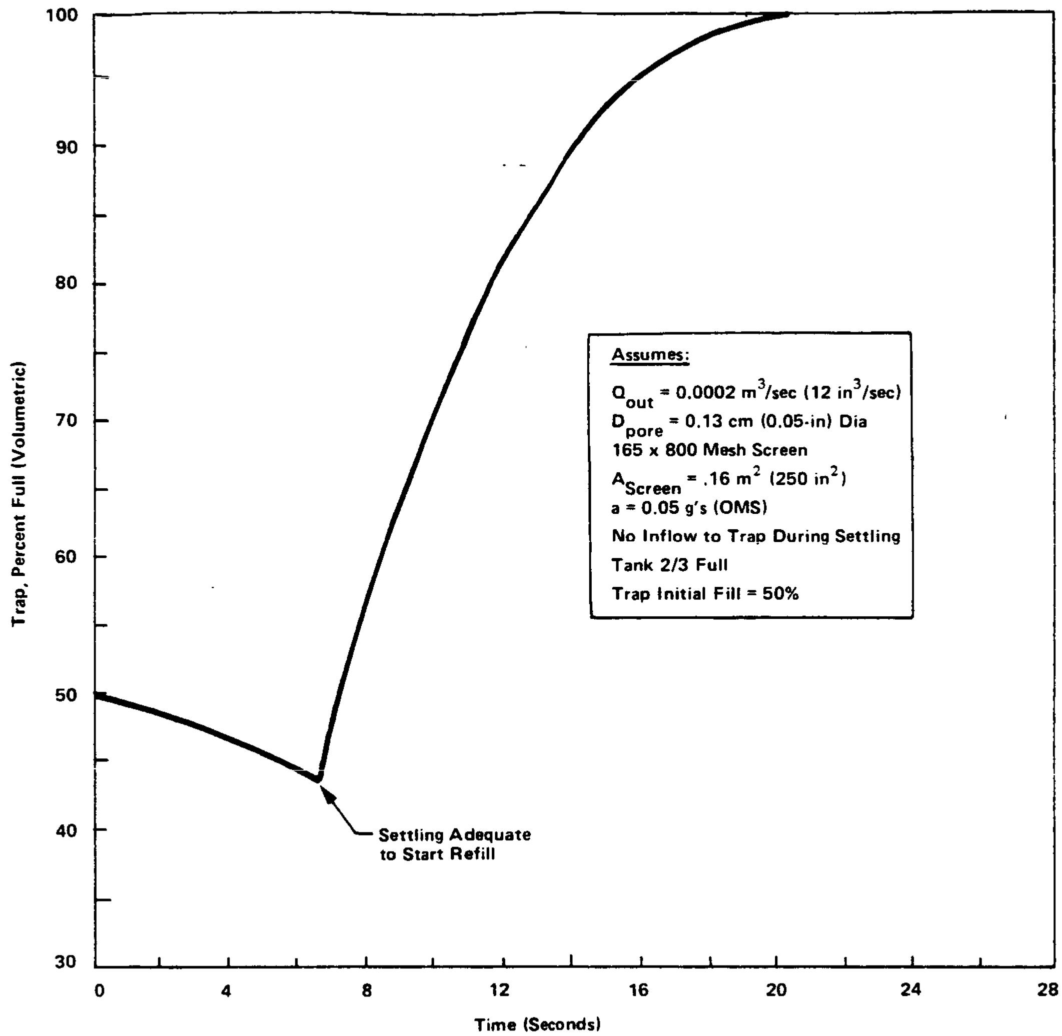



*Figure III-10 Predicted Refill of Partial Acquisition Device*

hydrostatic head, flow loss and capillary pressure, and adjusting flows accordingly. The settling time, assuming the tank is two-thirds full, is approximately 6 seconds. The trap is completely full by 19 seconds assuming it is initially half-full. The trap is designed to retain liquid under adverse axial and lateral accelerations.

## C. EXPERIMENT SIZING CONSIDERATIONS

In performing analyses for each of the fluid management systems, the phenomena and governing equations were examined to determine whether constraints exist that dictate the minimum size of the experiment for which the results will be valid for application to full size spacecraft design. As noted previously, it is imperative that the experiment be in the same behavior regime of the various dimensionless parameters of concern as the full scale application, and this requirement is one of the important criteria in experiment sizing. In most of the phenomena to be investigated, size enters into the governing relationships and it is desirable to have data from more than one experiment size to assure that these relationships properly account for size. In the case of receiver tank chilldown, two tank sizes are recommended to accomplish this purpose. It is also obviously desirable to keep the range of extrapolation to a reasonable value, in order that errors are not magnified and significant effects overlooked. In the case of no-vent fill experiments, it is imperative that the receiver tank be sized so that sufficient liquid is available to completely fill the tank. This will assure that effects due to the reduction of liquid-vapor interfacial area as the tank nears full are examined. No other specific limitations on the size of the various experiments to be included in the CFMF were identified.

For the mission two and three receiver tanks that will investigate no-vent fill, the capacity of the previously defined supply tank is adequate to meet experiment objectives. The receiver tank sizing summary is shown in Table III-1. The resulting size of these tanks gives a volume of 0.425 $m^3$ (15.1 cu-ft). The tank diameter is 77.8 cm (30.6 in.), and the length is 108.1 cm (42.54 in.) when geometrically scaled to the Boeing space-based OTV (NASA CR-3535). This is a linear scale factor of 0.18. The receiver tank for mission one, which is primarily designed to investigate tank chilldown, is sized to give a reasonable size difference between it and the mission two tank, which will also investigate tank chilldown. This tank size was selected as 121.9 cm (48 in.) diameter or 0.28 scale, based on the maximum practical size mounting considerations for the standard Shuttle carriers (Pallet and MPESS) with the overall proposed CFMF layout.

*Table III-1 Receiver Tank Sizing Summary*

| | |
|---|---|
| Supply Tank Volume: | 0.622 $m^3$ (22.0 $ft^3$) |
| Reductions: | |
| 10 percent max ullage | 0.62 $m^3$ (2.2 $ft^3$) |
| 1 percent expulsion losses | 0.006 $m^3$ (0.22 $ft^3$) |
| TVS operation 0.034 kg/hr (.075 lb/hr) for 48 hrs = 1.6 kg (3.6 lb) | 0.024 $m^3$ (0.84 $ft^3$) |
| Transfer Line Chilldown Losses 1.20 kg (2.65 lb) | 0.018 $m^3$ (0.62 $ft^3$) |
| Receiver Tank Chilldown Loss 4.5 kg (9.9 lb) | 0.066 $m^3$ (2.32 $ft^3$) |
| Remaining in Lines | 0.001 $m^3$ (0.02 $ft^3$) |
| Margin: | |
| 5 percent of Receiver Tank | 0.021 $m^3$ (0.75 $ft^3$) |
| Total Reductions and Margin: | 0.197 $m^3$ ( 6.97 $ft^3$) |
| Resulting Receiver Tank volume: | 0.425 $m^3$ (15.03 $ft^3$) |

## D. MISSION OBJECTIVES, SCHEMATICS AND TIMELINES

The mission objectives and technologies/systems to be verified by analytical model on each of the missions are itemized in Tables III-2 through III-5. The primary focus on Mission 1 is supply tank (total acquisition device and thermodynamic vent system) performance in low-g, and 0.28 scale receiver tank chilldown. Mission 2 concentrates on 0.18 scale receiver tank chilldown and no-vent fill. Mission 3 evaluates 0.18 scale receiver tank chilldown and no-vent fill when there is a partial acquisition device within the receiver, in addition to partial acquisition device thermal, settled-refill and expulsion performance. A cross reference showing which of the liquid storage/supply fluid management systems and technologies are recommended for investigation on each of the three missions is presented in Table III-6. Similar cross references for thermal control and fluid transfer/resupply are contained in Tables III-7 and III-8, respectively.

Preliminary simplified schematics for each of the three missions are included as Figures III-11 through III-13, respectively. In addition to a different receiver tank on each mission, the primary difference in the schematics is that two autogenous pressurant bottles are included for missions 2 and 3. Some plumbing interfaces with the receiver tanks are also modified due to the differences in configurations of the receiver tanks and associated heat exchangers, chilldown systems, etc.

Tentative mission timelines for each of the missions are shown in Figures III-14 through III-16. It should be noted that time durations represent allocations for investigating a process or technology. The specific process may occur over a portion of the allocated time.

*Table III-2 Mission 1 Objectives and Analytical Model Verification*

| CFMF MISSION 1 OBJECTIVES | | |
|---|---|---|
| | PRIMARY | SECONDARY |
| • CFME Supply Tank | o Evaluate supply tank total communication device, including capability with degraded insulation<br>o Evaluate supply tank quantity gaging system<br>o Evaluate thermal conditioning/outflow | o Demonstrate supply tank TVS<br>o Evaluate helium pressurization system |
| • Transfer Line<br>- Flow through childown<br>- Thermal simulated disconnect | o Obtain transfer line childown data - flow through<br>o Evaluate mass and quality metering | |
| • Receiver Tank<br>- 0.28 scale tank without acquisition device<br>- Internal spray nozzles or jets (minimum of two approaches, one tangential and one axial) | o Investigate receiver tank childown using internal spray nozzles or jets | o Purged MLI performance<br>- minimum 30 layers<br>- interstitial pressure measurement<br><br>CONTINGENCY<br>o Evaluate receiver tank partial fill if adequate fluid is available<br>o Evaluate tank venting of helium from partially full tank (preliminary) |

| CFMF MISSION 1 ANALYTICAL MODEL VERIFICATION | | |
|---|---|---|
| PRIMARY | SECONDARY | CONTINGENCY |
| o CFME supply tank performance (pressurization, outflow, thermal control, thermal conditioning)<br>o Transfer line childown<br>o Receiver tank childown Performance-spray nozzle or jets in low-g | o Purged MLI performance | o Receiver tank partial fill<br>o Receiver tank venting |

*Table III-3 Mission 2 Objectives and Analytical Model Verification*

| CFMF MISSION 2 OBJECTIVES | | |
|---|---|---|
| | PRIMARY | SECONDARY |
| • CFME Supply Tank | o Evaluate refill of total communication device (using receiver tank as supply) during settling outflow of receiver tank<br>o Evaluate supply tank quantity gaging<br>o Autogenous pressurization | o Evaluate low-g liquid/vapor quality and mass flow measurement |
| • Transfer Line | o Obtain transfer line childown data<br>o Evaluate mass and quality metering | |
| • Receiver Tank<br>- 0.18 scale tank without acquisition device<br>- Internal spray nozzles or jets (preferred approach from Mission 1)<br>- On-wall TVS (one at each end) | o Investigate receiver tank childown<br>o Evaluate no-vent fill to maximum fill level<br>o Perform outflow from receiver with helium pressurization and RCS settling to leave some liquid in receiver<br>o Evaluate venting of partially full receiver tank (i.e. venting of non-condensible) | o Receiver tank storage performance (operation of on-wall TVS)<br>o Evaluate passive stratification control<br>o Purged MLI performance |

| CFMF MISSION 2 ANALYTICAL MODEL VERIFICATION | |
|---|---|
| PRIMARY | SECONDARY |
| o Supply tank thermal conditioning of outflow with autogenous pressurization<br>o Transfer line childown<br>o Receiver tank childown<br>o Receiver tank no-vent fill<br>o Transfer system model<br>o Venting of gaseous helium from partially full tank<br>o Supply Tank Refill | o CFME supply tank performance<br>o Stratification control (passive - TVS)<br>o Receiver tank thermal performance<br>- insulation<br>- passive TVS |

*Table III-4 Mission 3 Objectives*

| CFMF MISSION 3 OBJECTIVES | | |
|---|---|---|
| | PRIMARY | SECONDARY |
| • CFME Supply Tank | o Evaluate refill of total communication device (using receiver tank as supply) during settling outflow of receiver tank immediately after receiver tank fill<br>o Evaluate supply tank quantity gaging<br>o Autogenous pressurization (open, pending Mission 2 results) | o Evaluate low-g liquid/vapor quality and mass flow measurement |
| • Transfer Line | o Obtain transfer line chilldown data<br>o Evaluate mass and quality metering | |
| • Receiver Tank<br>- 0.18 scale tank, and refillable partial acquisition device with TVS<br>- TVS either on wall or internal (mixer) at pressurant end<br>- Internal spray nozzles or jets (preferred approach from Missions 1 and 2)<br>- Foam insulation under MLI | o Evaluate chilldown and no-vent fill of tank with partial acq dev<br>o Perform outflow from receiver acq. device with helium, leaving some liquid in receiver<br>o Evaluate on-wall TVS thermal control performance, including thermal (stratification) for condition of bulk fluid positioned away from acquisition device<br>o Evaluate performance (if design constraints permit) of partial acquisition device<br>- TVS performance on device<br>- Capability to retain liquid while surrounded by vapor<br>- Refill with settled liquid (if design constraints permit)<br>o Evaluate venting of partially full tank (i.e. venting of non-condensibles) | o Receiver tank storage performance (foam-MLI performance)<br>o Evaluate helium pressurization of tank with partial acquisition device<br>o Evaluate transfer refill (from supply tank) of partial acquisition device |

*Table III-5 Mission 3 Analytical Model Verification*

| PRIMARY | SECONDARY |
|---|---|
| o Receiver tank (with acquisition device) childown<br>o Receiver tank no-vent fill<br>o Partial acquisition device performance (outflow, refill during settling, acquisition device TVS)<br>o Venting of gaseous helium from partially full tank<br>o Transfer system model<br>o Supply tank thermal conditioning of outflow with autogenous pressurization (if investigated on this mission)<br>o Stratification control (passive-TVS and/or active-mixer) | o CFME supply tank performance<br>o Receiver tank pressurization & outflow performance<br>o Refill of partial acquisition device (from supply tank) assuming design constraints permit an acceptable purging of gaseous helium pressurant from device<br>o Foam-MLI performance |

*Table III-6 Liquid Storage/Supply Fluid Management-Mission Cross Reference*

| | Priority Assessment | Mission 1 | Mission 2 | Mission 3 |
|---|---|---|---|---|
| • Fluid Management Systems | | | | |
| Acquisition/Expulsion Systems | | | | |
| Direct outflow with settling | 2 | X | X | |
| Total Communication Device | 1 | X | X | X |
| Partial Communication Device | 2 | | | X |
| Pressurization Systems | | | | |
| Ambient Helium | 2 | X | X | X |
| Cryo-cooled Helium | 3 | | | |
| Autogenous | 1 | | X | (X)* |
| Slosh Control Systems | 2 | | | |
| • Additional Technology Issues | | | | |
| Start Transients | 2 | X | X | X |
| Outage/Pullthrough | 3 | X | X | |
| Mass Gaging/Instrumentation | 1 | X | X | X |
| Non-conventional Tankage | 2 | | | |

* Parenthesis indicates that inclusion of particular technology is dependent on results of previous mission(s).

*Table III-7 Thermal Control System - Mission Cross Reference*

| | Priority Assessment | Mission 1 | Mission 2 | Mission 3 |
|---|---|---|---|---|
| • Thermal Protection Systems | | | | |
| Vacuum Jacket/Insulation (dewar) | 3 | X | X | X |
| Purged - MLI | 2 | X | X | |
| Foam - MLI | 2 | | | X |
| • Thermal Management Systems | | | | |
| Thermodynamic Vent Systems | | | | |
| Internal Heat Exchanger | 1 | | X | X |
| External Heat Exchanger (including vapor-cooled shield) | 1 | X | X | X |
| Coupled Heat Exchanger (vent-free storage) | 2 | | | |
| Para-to-ortho Conversion | 2 | | | |
| Direct Tank Venting with settling | 3 | (X)* | X | X |
| Refrigeration Systems | | | | |
| • Additional Technology Issues | | | | |
| Insulation Reusability (non-dewar) | 2 | | | |
| Insulation Degradation (with time) | 1 | | | |
| Supports/Lines/Penetration Heat Leaks | 3 | X | X | X |
| Thermal Acoustic Oscillations | 3 | | | |
| Convection Control | 3 | | X | X |
| Thermal Conditioning Outflow | 1 | X | X | X |

* Parenthesis indicates contingency mission event if other objectives are accomplished and time line permits.

*Table III-8 Fluid Transfer/Resupply Technologies - Mission Cross Reference*

| | Priority Assessment | Mission 1 | Mission 2 | Mission 3 |
|---|---|---|---|---|
| ● Receiver Tank | | | | |
| Empty | | | | |
| Childown | 1 | X | X | X |
| Acquisition Device Fill | 1 | | (X)*** | X |
| Vapor Collapse | 1 | | (X)*** | X |
| Purge, Non-Condensibles | 1 | | | X |
| No-Vent Fill | 1 | (X)* | X | X |
| Partially Full | | | | |
| Venting Non-Condensible | 1 | (X)** | X | X |
| No-Vent Fill | 1 | | X | X |
| Vented Fill | 2 | | | |
| ● Transfer Line | | | | |
| Childown | 1 | X | X | X |
| Quick Disconnect (thermally simulated) | 1 | X | X | X |
| ● Additional Technology Issues | | | | |
| Mass Gaging | 1 | X | X | X |
| Mass/Quality Metering | 1 | X | X | X |
| Pump vs. Pressurized Transfer | 2 | | | |
| Long Term Effects | | | | |
| Repeated Cycling Degradation | 3 | | | |
| Contamination | 3 | | | |

* Evaluation of receiver tank partial fill if adequate fluid is available.
** Preliminary evaluation of receiver tank venting if partial fill is accomplished
*** Supply Tank Refill

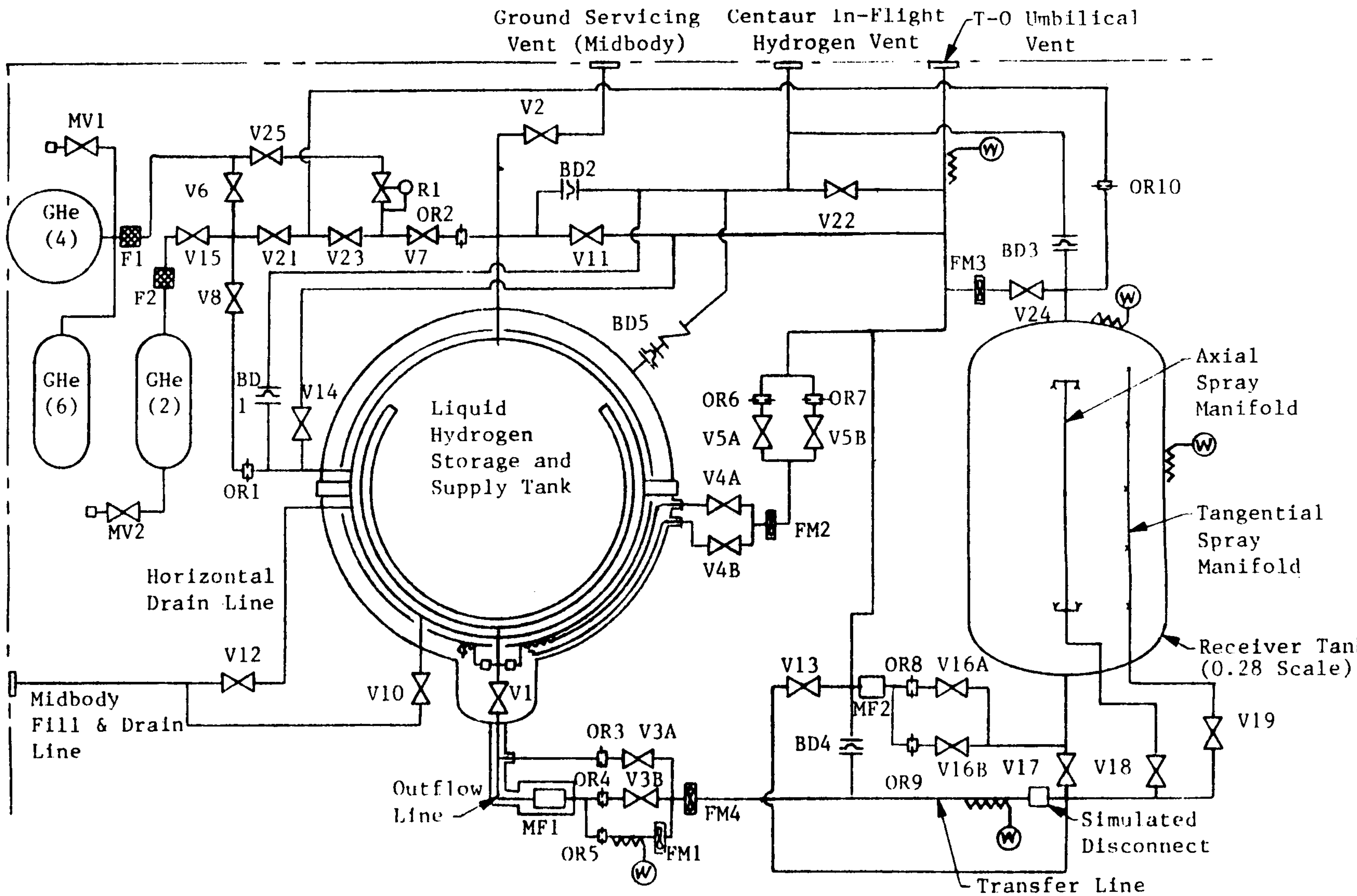



*Figure III-11 Mission 1 Simplified Schematic*

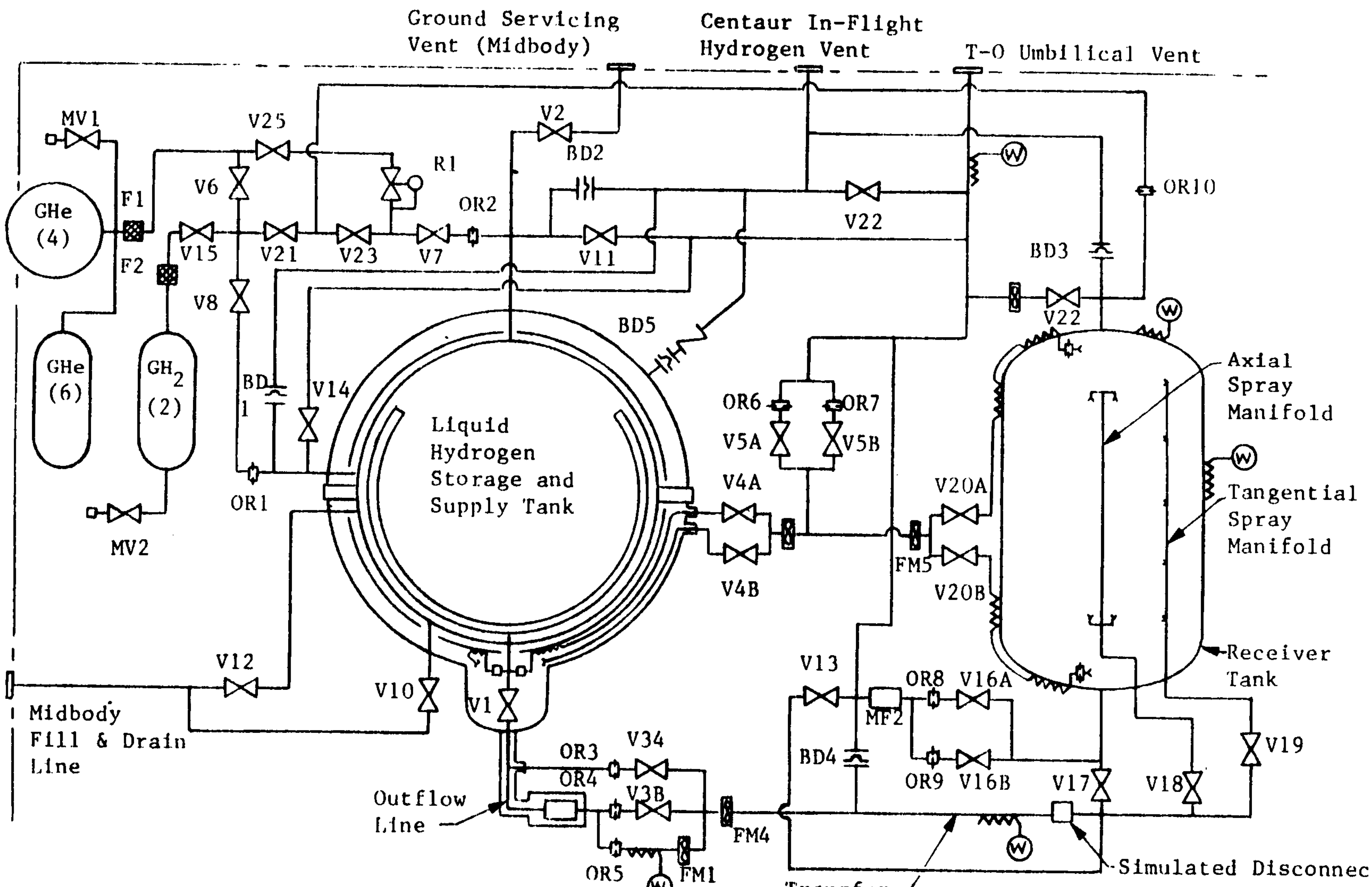



*Figure III-12 Mission 2 Simplified Schematic*

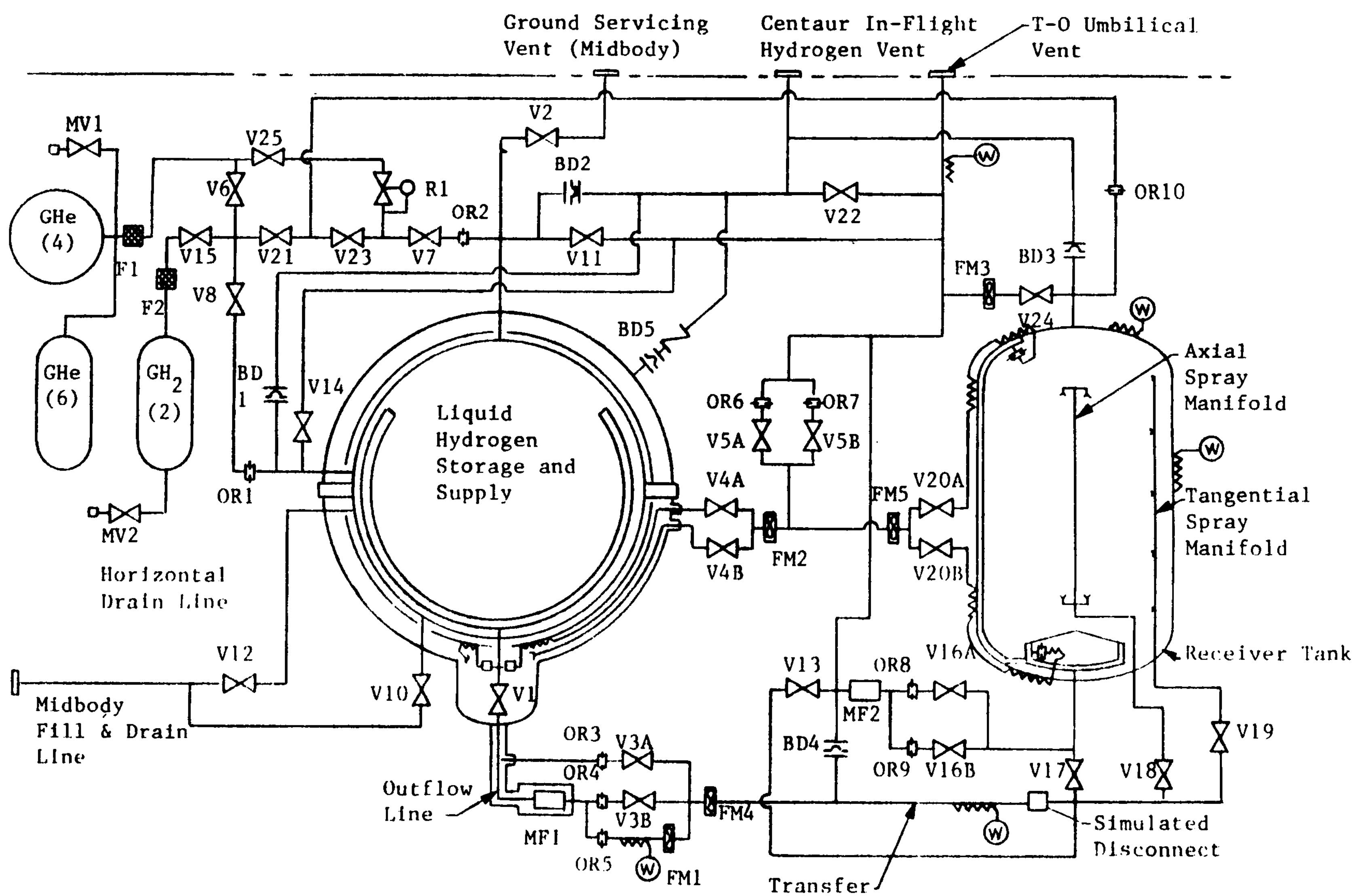



*Figure III-13 Mission 3 Simplified Schematic*

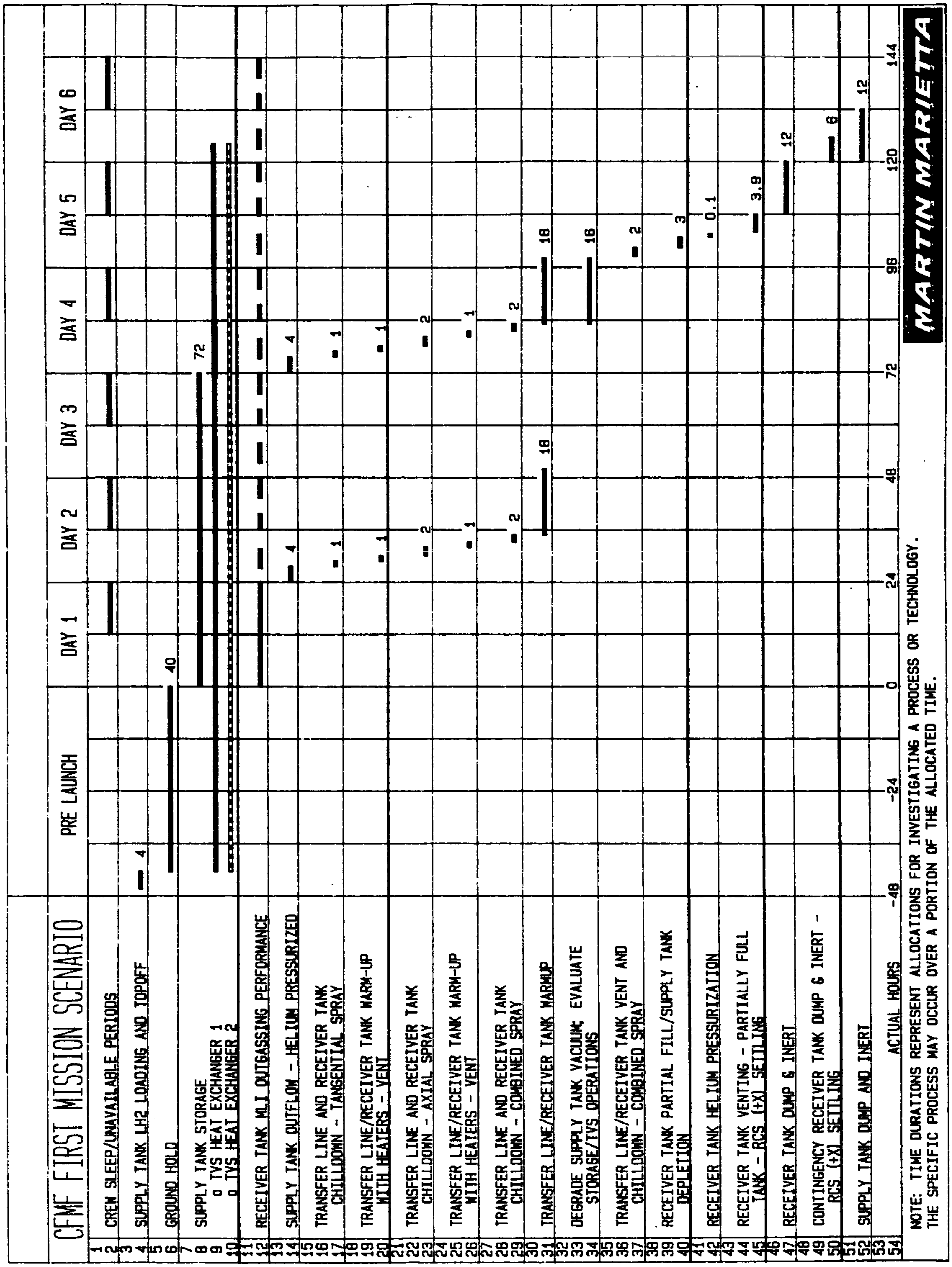



*Figure III-14 Mission 1 Timeline*

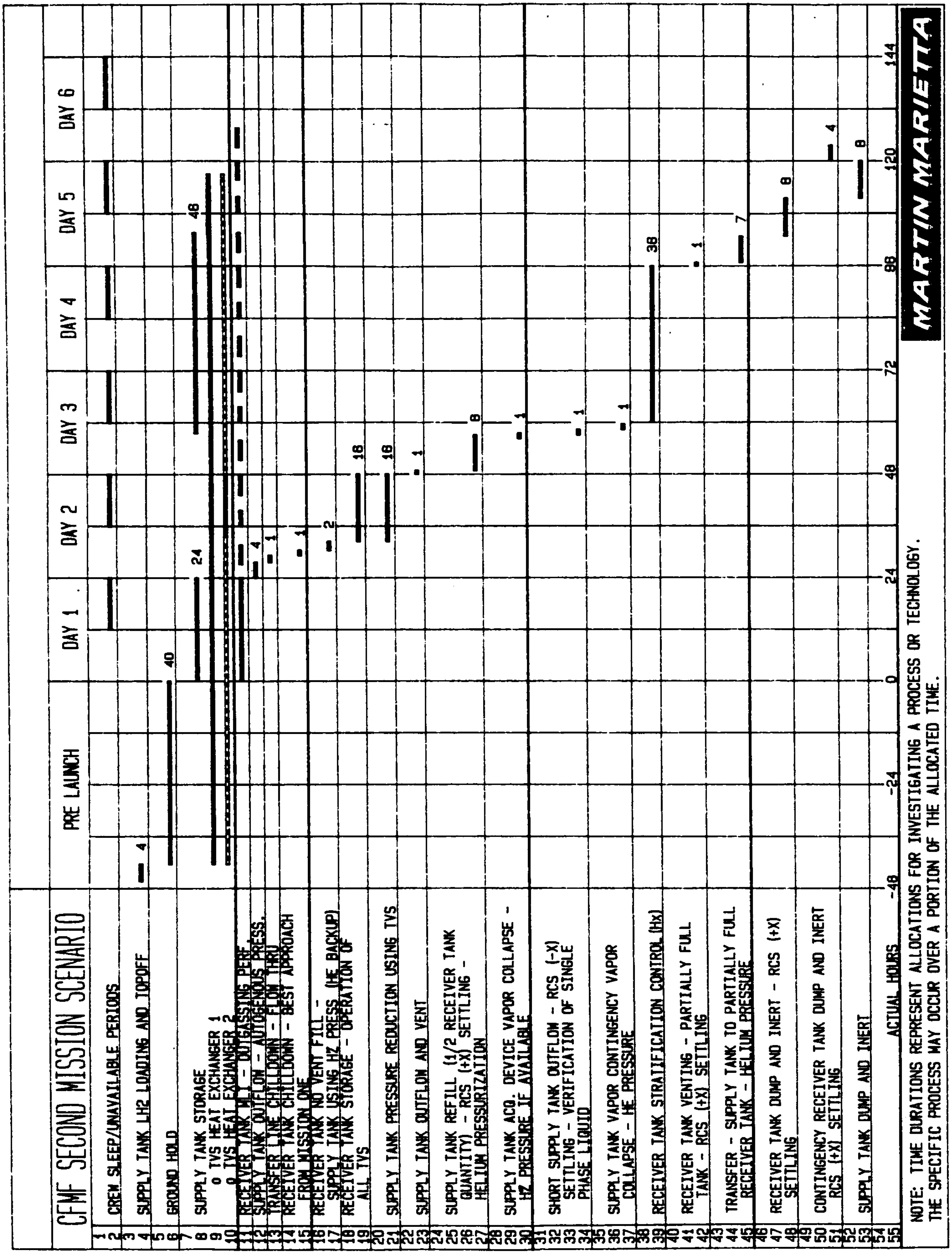



*Figure III-15 Mission 2 Timeline*

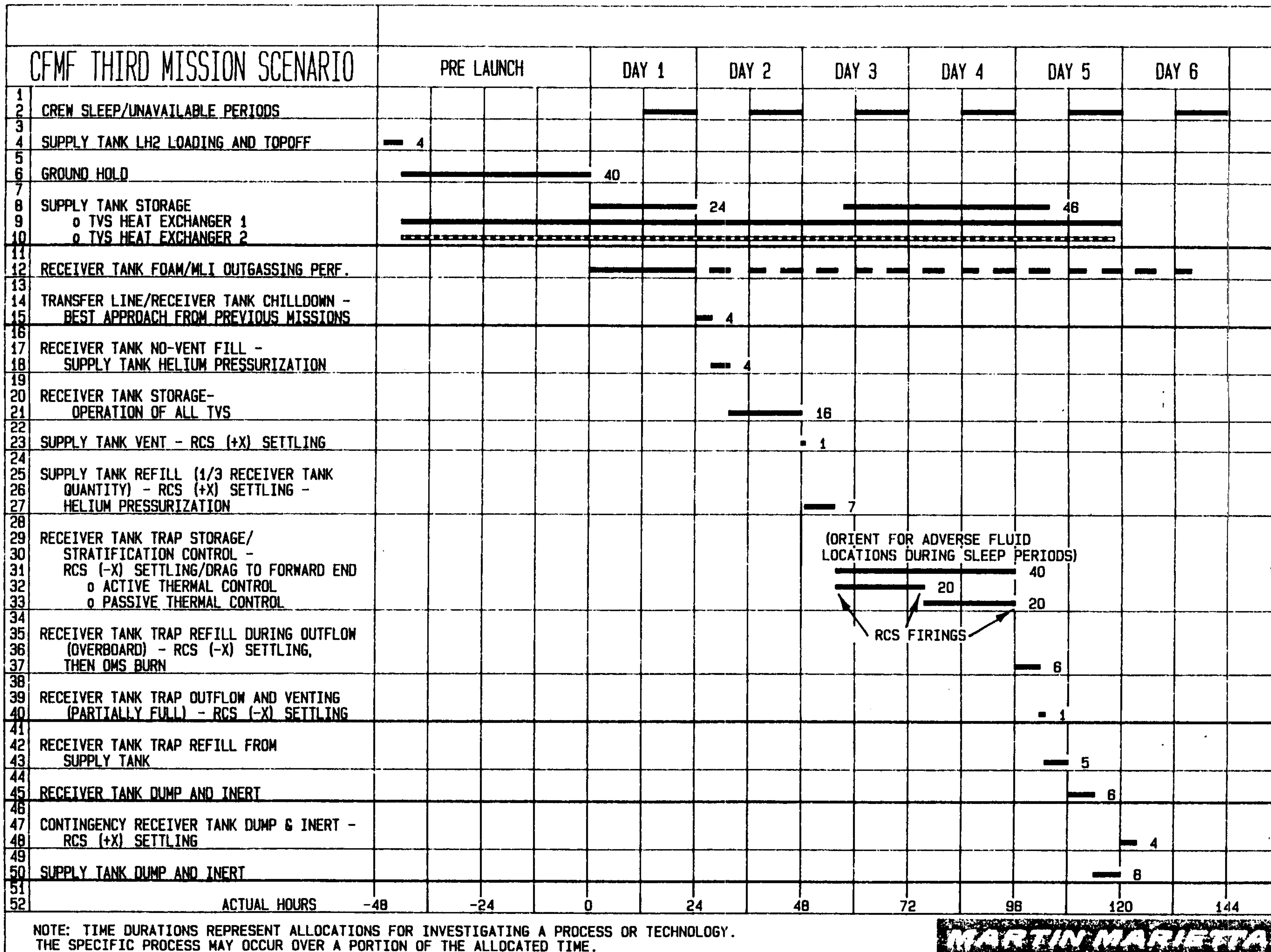



*Figure III-16 Mission 3 Timeline*

## IV. CFMF CONCEPTUAL DESIGN STUDIES

CFMF conceptual design studies were conducted considering potential modifications to the previously defined systems concepts described in NASA CR-165279 and NASA CR-165495. Two potential carriers were evaluated, the Spacelab pallet and the Multipurpose Experiment Support Structure (MPESS). Two specific Spacelab pallet configurations were evaluated, the European Space Agency (ESA) pallet with Igloo avionics package, and the MDM pallet, which is the mixed cargo carrier version of the Spacelab pallet. Representations of the CFMF on the MPESS and MDM pallet are shown in Figures IV-1 and IV-2, respectively.

Preliminary structural and thermal design trades were made, CFMF/carrier integration, ground processing, and flight opportunity assessments were made for each configuration, and a ROM cost and schedule for development and three flights were prepared. These trade studies are discussed below, and the recommended CFMF conceptual design and preferred carrier resulting from this effort is presented in Chapter V.

### A. STRUCTURAL DESIGN TRADES

The structural design trade studies focused on the mechanical interface requirements for each support structure, and included dynamic environments, stiffness requirements, structural attachments, and load carrying capability. Requirements for structural qualification and certification were also addressed in order to identify any related concerns of the support structure which might impact project cost and/or complexity.

Dynamic Environments - Carrier environmental and design load requirements were very similar. Tables IV-1 and IV-2 present a comparison of the requirements for the Spacelab pallet, the MDM pallet and the MPESS. Although the MDM pallet is a Spacelab pallet with modified subsystems, the environmental requirements for this carrier have been updated to reflect STS flight experience. It is anticipated that the Spacelab Payload Accommodations Handbook (SLP/2104) will be updated to reflect the same requirements for the Spacelab pallet. (Since the Spacelab pallet and MDM pallet have the same pallet support structure and hardpoints, they will be referred to as a pallet in the paragraphs below, as contrasted with the MPESS carrier).

Both the MPESS and pallet carriers require a payload fundamental frequency greater than or equal to 25 Hz. Preliminary dynamic analyses conducted on both CFMF configurations indicated that this requirement could be met for either carrier. In addition, the MPESS requires that the fundamental mode of the overall carrier/payload system be 10 Hz $\pm 2$ Hz. The MPESS has removable truss members to allow tuning of the system dynamics. Compliance with this requirement could not be assessed at this time. The requirement has been levied in order to avoid high MPESS loads due to coupling with STS transient events.

Structural Interfaces - The CFMF structural interface with the MPESS is significantly more complicated than the CFMF/pallet interface. Attachment of payloads to the MPESS is made via gusset plates on the upper box truss of the support structure. The gusset plates can only be loaded in shear (no tension loads are allowed). Each gusset plate has six-5/16 in. holes for attachment. Dimensional tolerances between holes on the same gusset plate and adjacent gusset plates on the same truss face are controlled. However, tolerances between holes or different truss faces are not controlled. Our CFMF design concept interfaces with 18 gusset plates and 72 holes on three truss faces.

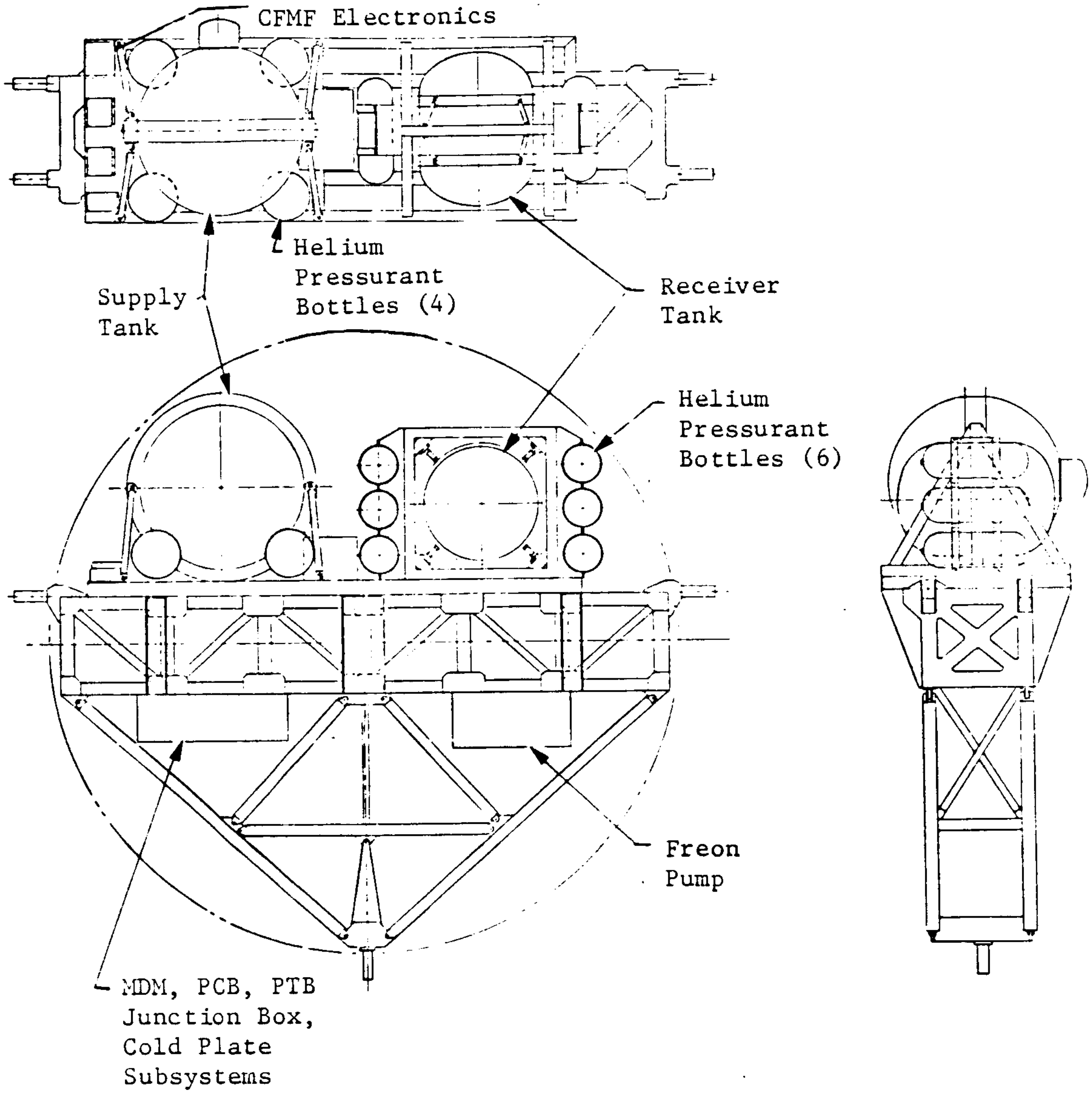



*Figure IV-1 CFMF/MPESS Configuration*

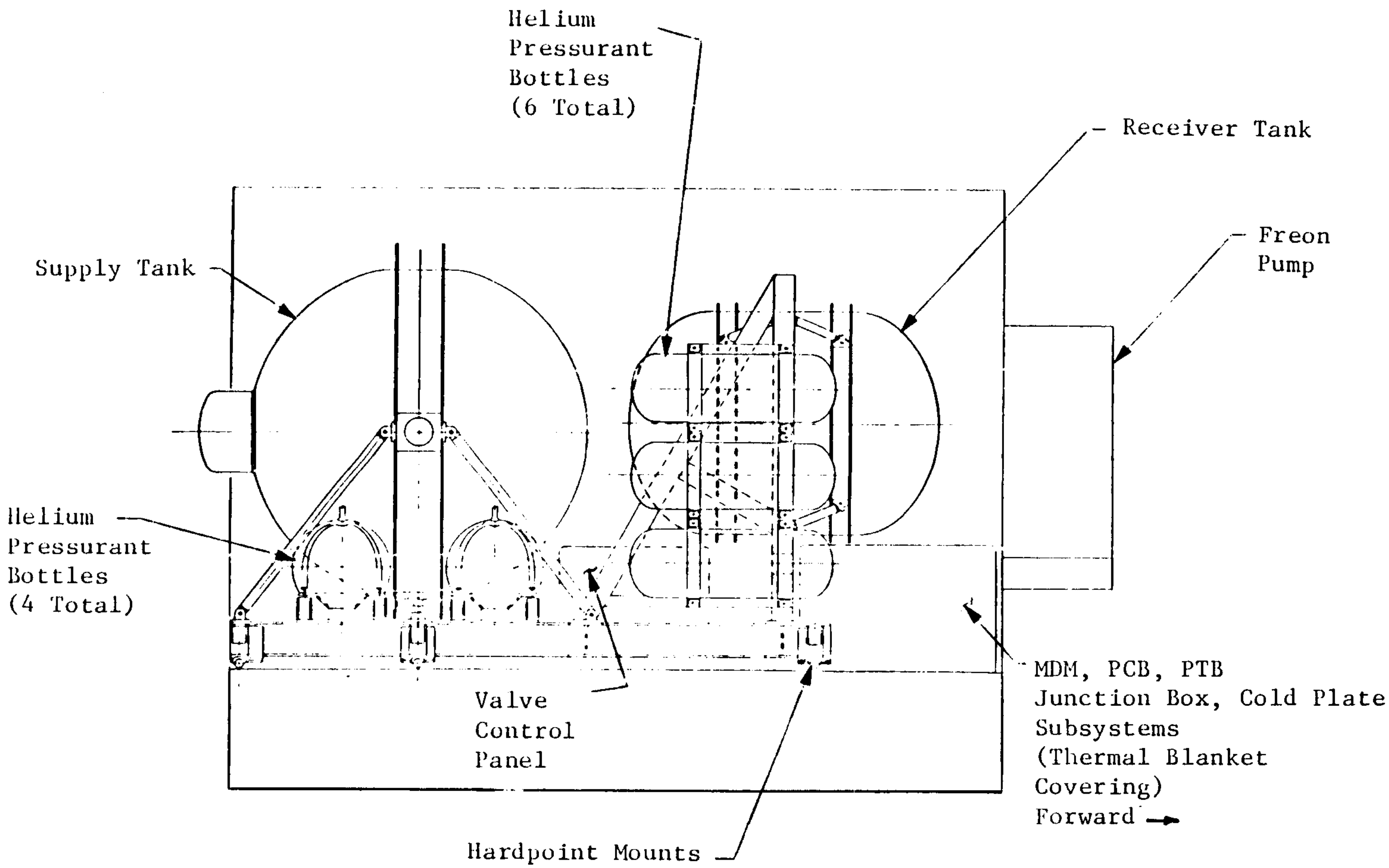



*Figure IV-2 CFMF/MDM Pallet Configuration*

*Table IV-1 Carrier Environmental Requirements Comparison*

- Component Sinusoidal Vibration (Input g; o-peak)
  - Sweep at 3 Oct/Min

Spacelab Pallet

| Freq(Hz) | X | Y | Z |
|---|---|---|---|
| 5-8.5 | 0.8"DA | 0.8"DA | 0.8"DA |
| 8.5-35 | 3.0 | 3.0 | 3.0 |
| 35-50 | 1.0 | 0.0 | 0.0 |

MDM Pallet

| Freq(Hz) | X | Y | Z |
|---|---|---|---|
| 5-11 | 1.0 | 1.0 | 1.0 |
| 11-25 | 3.6 | 1.3 | 4.3 |
| 25-50 | 1.0 | 1.0 | 1.0 |

MPESS

| Freq(Hz) | X | Y | Z |
|---|---|---|---|
| 5-15 | 1.0 | 1.0 | 1.0 |
| 15-25 | 4.7 | 2.2 | 5.7 |
| 25-50 | 1.0 | 1.0 | 1.0 |

- Induced Environment-Random Vibration

Spacelab Pallet

| Freq(Hz) | Level ($g^2$/Hz) |
|---|---|
| 20 | 0.00024 |
| 20-150 | +9 db/oct |
| 150-600 | 0.1 |
| 600-2000 | -9 db/oct |
| 2000 | 0.0027 |
| Composite = 8.72 grms | |

50 Sec + 20 Sec/Mission

MDM Pallet

| Freq(Hz) | Level($g^2$/Hz) |
|---|---|
| 20 | 0.00062 |
| 20-150 | +6 db/oct |
| 150-400 | 0.035 |
| 400-2000 | -9 db/oct |
| 2000 | 0.00028 |
| Composite = 4.1 grms | |

100 Sec + 50 Sec/Mission

MPESS

| Freq(Hz) | Level($g^2$/Hz) |
|---|---|
| 20 | 0.0022 |
| 20-100 | +6 db/oct |
| 100-400 | 0.056 |
| 400-2000 | -6 db/oct |
| 2000 | 0.0022 |
| Composite = 6.1 grms | |

50 Sec + 20 Sec/Mission

- Induced Environment-Acoustics

| Spacelab Pallet | MDM Pallet | MPESS |
|---|---|---|
| 145 db Overall | 138.5 db Overall | 145 db Overall |

Note: MDM pallet requirements from Feb 1983 PDR Data Package; Spacelab pallet requirements from SLP/2104, which will be updated to reflect STS OFT pallet flight data. No flights of MPESS to date.

*Table IV-2 Payload Frequency Criteria and Design Limit Load Factors*

| Requirement | Spacelab Pallet* | | | MDM Pallet** | | | MPESS # | | |
|---|---|---|---|---|---|---|---|---|---|
| Payload Freq. | | | | | | | | | |
| - Mounted to hard points | 25 Hz | | | 25 Hz | | | 25 Hz | | |
| - Mounted to secondary structure | 35 Hz | | | 35 Hz | | | 35 Hz | | |
| - Overall carrier plus payload | N/A | | | N/A | | | 10 Hz ± 2 Hz | | |
| Quasi-Static Design Loads | Acceleration (g) | | | Acceleration (g) | | | Acceleration (g) | | |
| | X | Y | Z | X | Y | Z | X | Y | Z |
| Liftoff | +2.11 -4.3 | ±1.4 | +5.5 -6.1 | -2.0 -5.0 | ±1.5 | +4.7 -4.5 | +2.3 -4.8 | ±2.7 | ±5.9 |
| Landing | ±4.0 | ±1.0 | +6.6 -4.0 | +3.8 -4.5 | ±1.6 | +6.0 -3.0 | ±6.6 | ±3.0 | +8.0 -5.0 |

* SLP/2104, Spacelab Payload Accommodation Handbook
** MDC H0314, Spacelab Pallet System Structural Design Criteria
\# JA-136, OSTA-2 Partial Payload Integrated Payload Requirements Document

*Table IV-3 MPESS Carrier and CFMF Weight and CG Comparisons*

| Payload | PL + MPESS Weight (lb) | Payload CG (In.) x | y | z |
|---|---|---|---|---|
| Option 1 (1) | 3885 | -17.8 | 3.8 | 7.6 |
| Option 2 | 3685 | -28.1 | 8.1 | -11.9 |
| Option 3 | 5210 | -17.8 | 3.8 | 3.0 |
| OAST-1 (2) | 3880 | -1.07 | 1.0 | -14.0 |
| OSTA-2 (3) | 4697 | 5.4 | -2.6 | -2.6 |
| LFC (4) | 4000 | -6.37 | 12.87 | -10.75 |
| CFMF (5) | 3115 | -14.1 | 6.1 | -6.3 |

(1) Spec 81-4-0006-TBE-A, design and performance specification (CEI Part I), MPE support structure, CEI No. F43001A
(2) JA-135, OAST-1 partial payload IPRD. (STS-14)
(3) JA-136, OSTA-2 partial payload IPRD. (STS-7)
(4) Large format camera PDR data package. (STS-14)
(5) Estimated 2/83

Consequently the CFMF/MPESS interface must be match-drilled and tightly shimmed (to ensure gusset plates are not loaded in tension) to a particular MPESS.

The CFMF/pallet interface is fairly simple. The CFMF subpallet mounts to six inner longeron hardpoints. Although dimensional tolerances between hardpoints are fairly large, the CFMF/hardpoint interface is designed for shimming in three directions to accommodate hardpoint location variations from pallet to pallet.

Carrier Loading - Allowable payload/MPESS interface loads are not specifically defined. Users must define loads in the MPESS and an analysis must be performed by NASA/MSFC - Teledyne Brown to verify MPESS structural margins. However, the CFMF design falls within the envelope (weight and CG) of MPESS design-point payloads and currently manifested payloads as indicated in Table IV-3.

All pallet hardpoints carry x, y, and z loads. Loading capabilities are defined in SLP/2104. A preliminary analysis has been conducted which indicates that CFMF/pallet interface loads will be substantially less than stated capabilities. Additionally, the CFMF weight, estimated at 645 kg (1420 lb) at this point in the conceptual design task, is well within the pallet capability of 2886 kg (6349 lb).

Subsystem Accommodations - The CFMF requires power/communication, such as the Flex Multiplexer/Demultiplexer (FMDM), Power Control Box (PCB), Payload Timing Buffer (PTB), AC power, etc., and active thermal control, including a freon pump, cold plate(s), etc. Support structure/mounting provisions are provided for these subsystems on the Spacelab and MDM pallets. Payload users must design and fabricate subsystem support structures for the MPESS.

Structural Qualification/Certification - Carrier choice does not affect the test and analysis requirements for structurally qualifying the CFMF payload for flight (Ref. JSC-14046). However, assuming that neither carrier will be available for systems level testing, test fixturing for the MPESS will be more complex than for the pallet due to the carrier interface configuration. Use of either carrier will require a coupled-loads analysis to verify payload and carrier integrity. This is somewhat more critical for the MPESS since interface load capabilities are not specifically defined.

Structural Trade Summary - The structural evaluation did not identify any constraint or concern that would eliminate either carrier.

- The pallet and MPESS dynamic environments are similar.
  - We see no problem meeting the 25 Hz frequency criterion on either carrier.
  - A preliminary structural analysis of both CFMF configurations has confirmed the integrity of the basic structural arrangements.
- The CFMF/MPESS structural interface is more complex than the CFMF/pallet interface.
  - MPESS interface requires shimming and match drilling for a particular MPESS
  - MPESS interface includes 72 points compared to 8 for either pallet
  - MPESS interface load carrying capability not specifically defined; pallet capability is defined in SLP/2104.

- MPESS subsystem support structure must be designed and fabricated by user. Pallet supplies integrated subsystems with support structures.
- Test fixturing for MPESS will be more complex due to structural interface complexity.

## B. THERMAL DESIGN TRADES

Thermal trade studies between the MPESS carrier and the Spacelab or MDM pallet resulted in the pallet being recommended as the preferred carrier for the CFMF payload. The pallet offers the following benefits from a thermal standpoint:

- o The experiment can be skid mounted, resulting in a minimum thermal interface with the carrier.
- o The pallet design allows for more effective thermal isolation of the facility from the cargo bay. The conductive thermal path is through only 8 hard points for the pallet whereas the facility would have a significant surface area in direct contact with the MPESS, resulting in facility temperatures closely following those of the cargo bay.
- o A more reproducible thermal environment is attainable from flight to flight.
- o Three simple flat surfaces are presented for the installation of insulation blankets.
- o The pallet thermal requirements are better defined, resulting in a lower-risk design approach.
- o A simpler insulation support concept can be used.

The conceptual design of the CFMF thermal protection system is shown schematically in Figure IV-3. It requires a thermal blanket shrouding the pallet, with provisions for actively cooling and heating various components/elements within the resulting enclosure. The CFMF electronics will require active cooling.

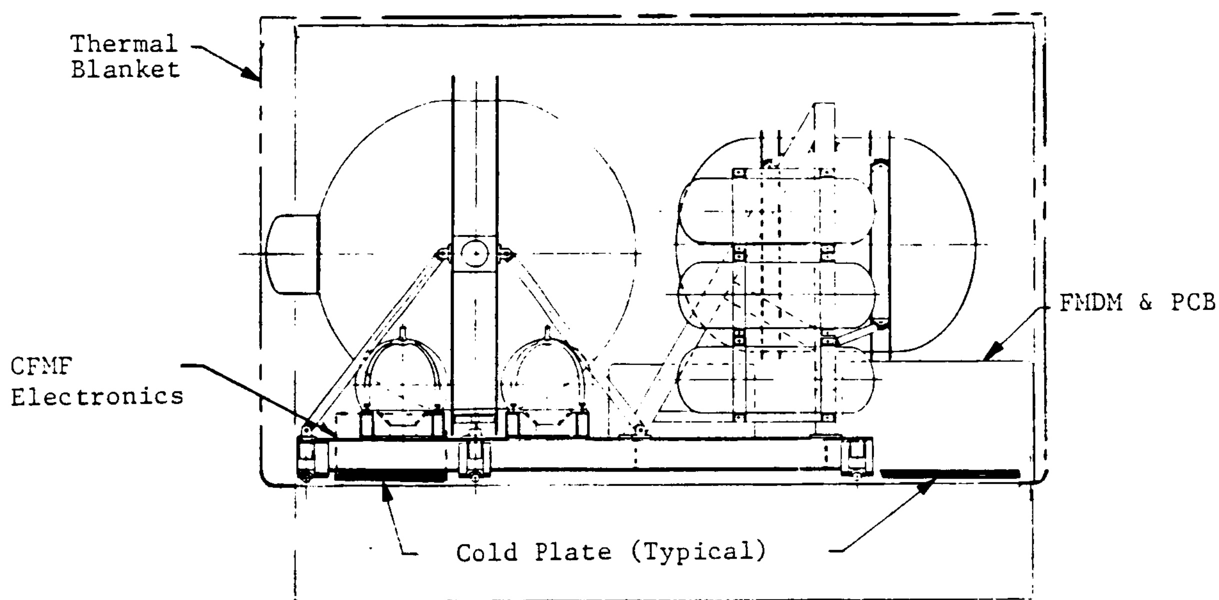



*Figure IV-3 Conceptual Design for CFMF/Pallet Thermal Protection System with Active Thermal Control*

Figures IV-4 and IV-5 show the preliminary performance of the thermal design under assumed worst-case hot and cold conditions, respectively. Electronics temperature limits were assumed to be 4.5°C (40°F) and 38°C (100°F). Under the assumed hot case conditions extended beyond 2 days, enclosure conditioning cold plates are required. Likewise, if the assumed worst-case cold exposure lasts for more than 3 days, heat (resistant heater) is required to maintain an assumed CFMF temperature requirement of 4°C (40°F).

## C. CONFIGURATION/CARRIER TRADES

In addition to structural design and thermal trade studies, other carrier considerations were evaluated, including integration complexity, avionics interfaces, launch processing, and the availability of flight opportunities.

CFMF/Carrier Systems Integration - The Orbiter standard accommodations are identical for the two carriers and are provided from the inventory (e.g. FMDM, PCB, freon pump, etc.). Integration of the CFMF onto the MPESS is complicated by the need to match-drill the interface to a particular carrier at KSC (pre-level IV integration). No support stand currently exists in the inventory for MPESS pre-level IV integration buildup.

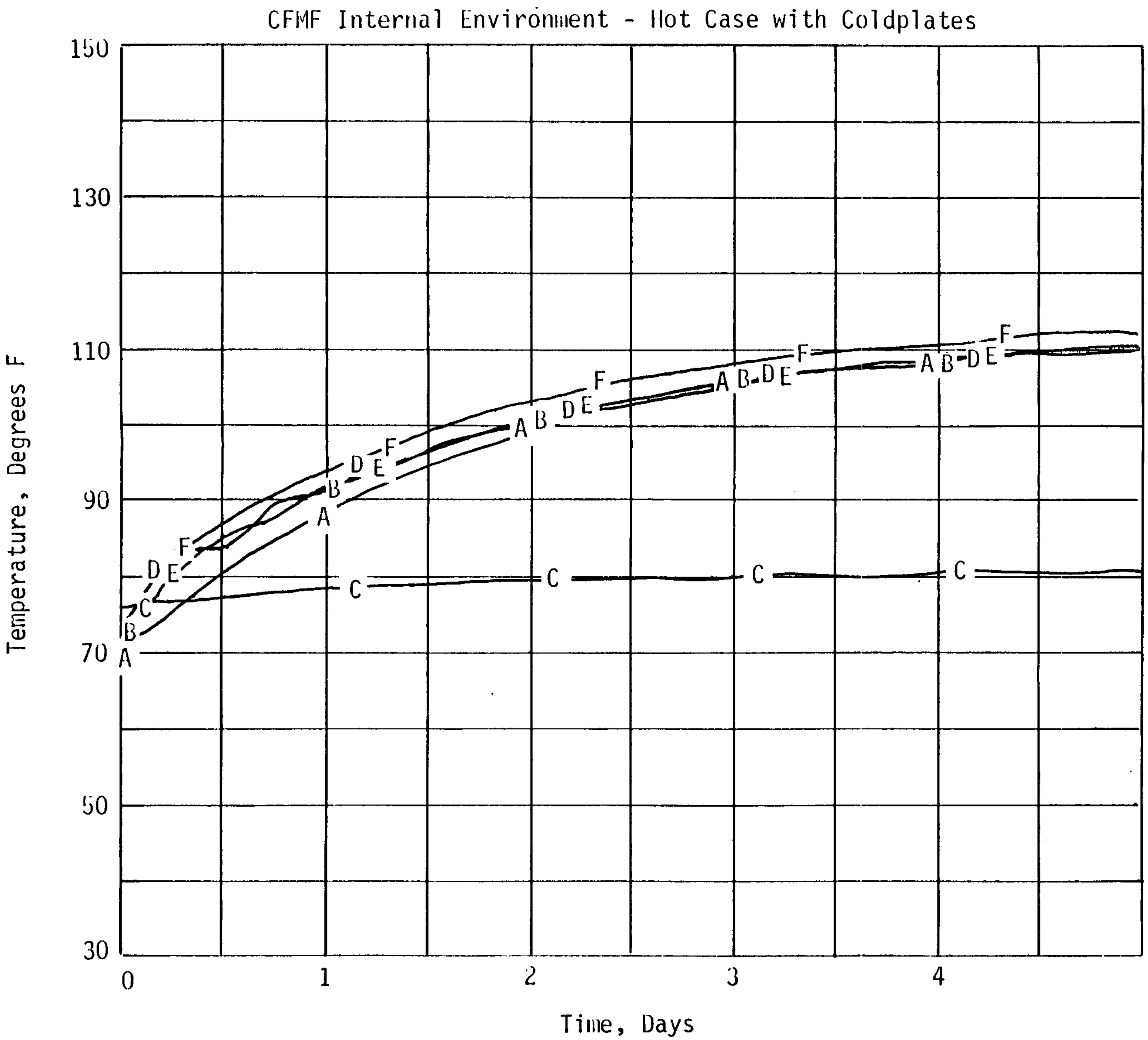
CFMF Avionics Interfaces - CFMF control and data acquisition system (CADS) interfaces with the Shuttle Orbiter and required carrier support subsystems, such as the MDM, PCB and PDI, were evaluated only to the extent required to identify any major drivers for selecting one carrier over another. The MPESS and MDM pallet avionics subsystems are identical, resulting in no specific carrier preference. The Spacelab pallet avionics interface is the Igloo, which introduces increased complexity, documentation submittals and interfaces. A preliminary block diagram of the CFMF/MDM Avionics package/Orbiter interfaces is shown in Figure IV-6. Redundancies are included in portions of the CFMF avionics, including the CADS, the power distribution units (PDU's) and the tape recorders (DTR's).

KSC Ground Processing - Ground processing at KSC is identical for both carriers. The processing flow at KSC, illustrated in Figure IV-7, is as follows:

- Build up horizontally in the Operations and Control (OandC) Building,
- Transport in cannister to the Orbiter Processing Facility (OPF) for installation in the Orbiter.
- Transport to the Pad for mating of umbilicals and loading of liquid hydrogen.

Integration meetings with KSC resulted in a change to the planned procedure for abort draining of liquid hydrogen after an RTLS abort. KSC prefers to drain through the midbody umbilical in the Orbiter Processing Facility (OPF), rather than through the T-0 umbilical to a burn stack on the runway.

Availability of Flight Opportunities - The carrier inventory consists of 10 Spacelab flight pallets and 5 MPESS structures (4 at MSFC, 1 at GSFC). The normal Spacelab pallet, with Igloo subsystems, requires two Orbiter cargo bay sections (The Orbiter is manifested by quarter cargo bay sections, minimum). In comparison, the MDM pallet system and MPESS require only one cargo bay section. Consequently both the MPESS and MDM pallet are 50 percent less costly (per flight) than the standard Spacelab pallet system.



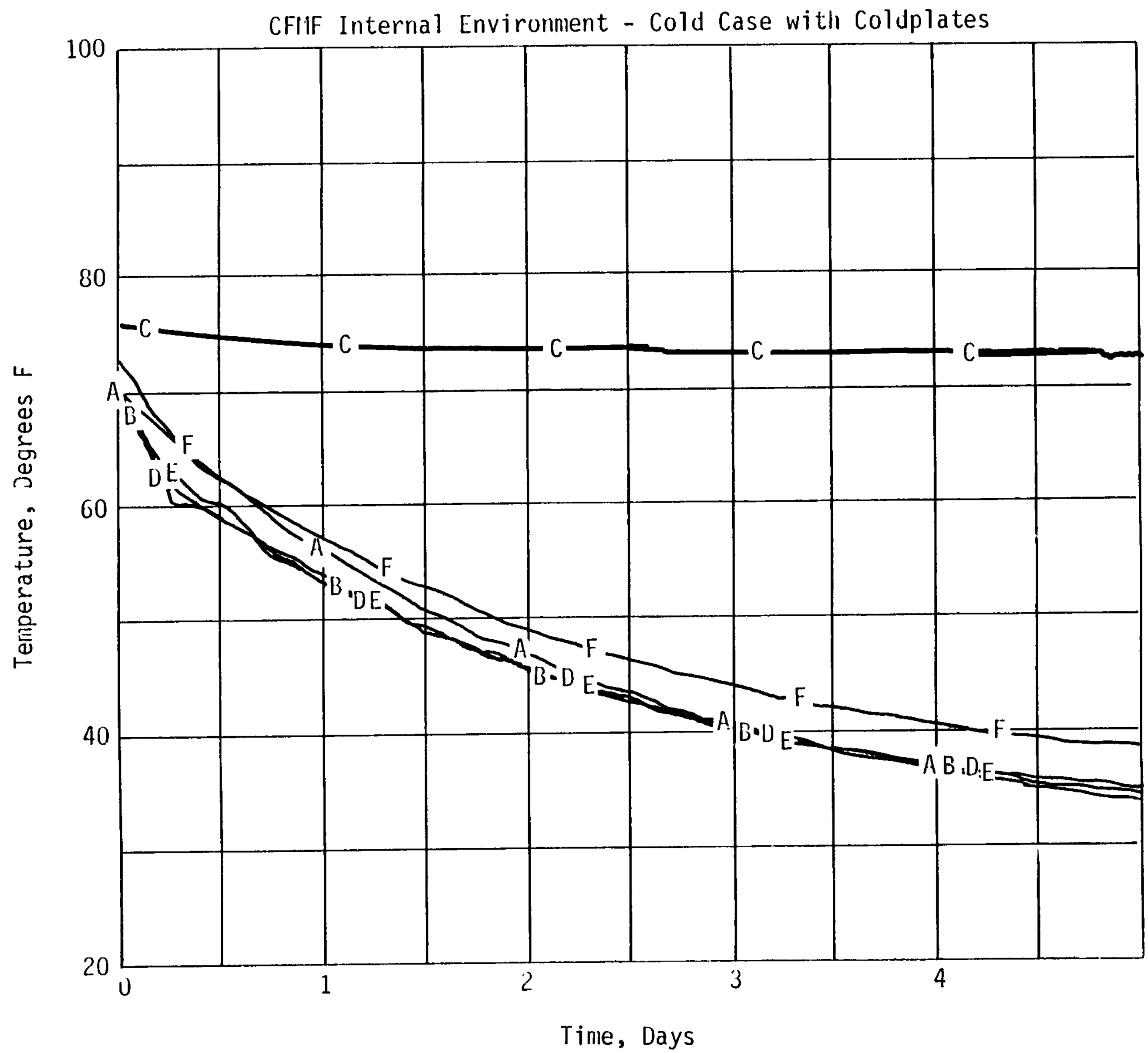

NOTES:

1. Start conditions - steady state in $70^{\circ}F$ environment.
2. Effective Blanket emittance - 0.03.
3. Cargo bay orientation Direct Solar, $\beta = 90^{\circ}F$.
4. No. of enclosure conditioning Coldplates = 5.
5. Average Coldplate temp. $70^{\circ}F$.

KEY:

A = Pallet
B = Supply Tank
C = CFMF Electronics
D = Avg. Radiant Temp.
E = Receiver Tank
F = Valve Box

*Figure IV-4 Thermal Performance - CFMF Conceptual Design - Hot Case*




NOTES:

1. Start conditions - steady state in 70°F environment.
2. Effective Blanket Emittance = 0.03.
3. Cargo bay orientation - Deep space.
4. No. of enclosure conditioning coldplates = 5.
5. Average Coldplate temp. 70°F.

KEY:

A = Pallet
B = Supply Tank
C = CFMF Electronics
D = Avg. Radiant Temp.
E = Receiver Tank
F = Valve Box

*Figure IV-5 Thermal Performance - CFMF Conceptual Design - Cold Case*

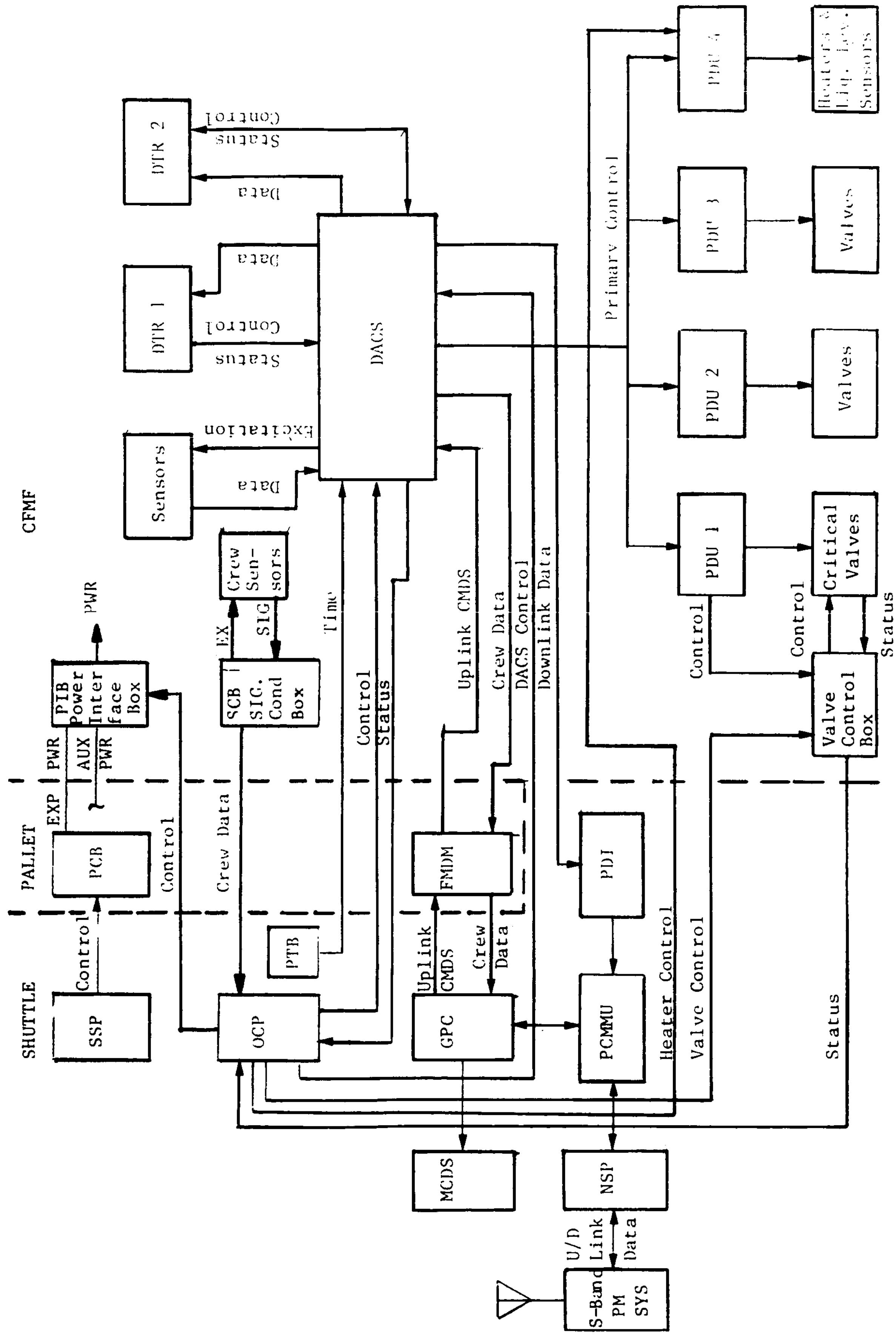



*Figure IV-6 Preliminary Orbiter/Carrier/CFMF Avionics Interfaces*

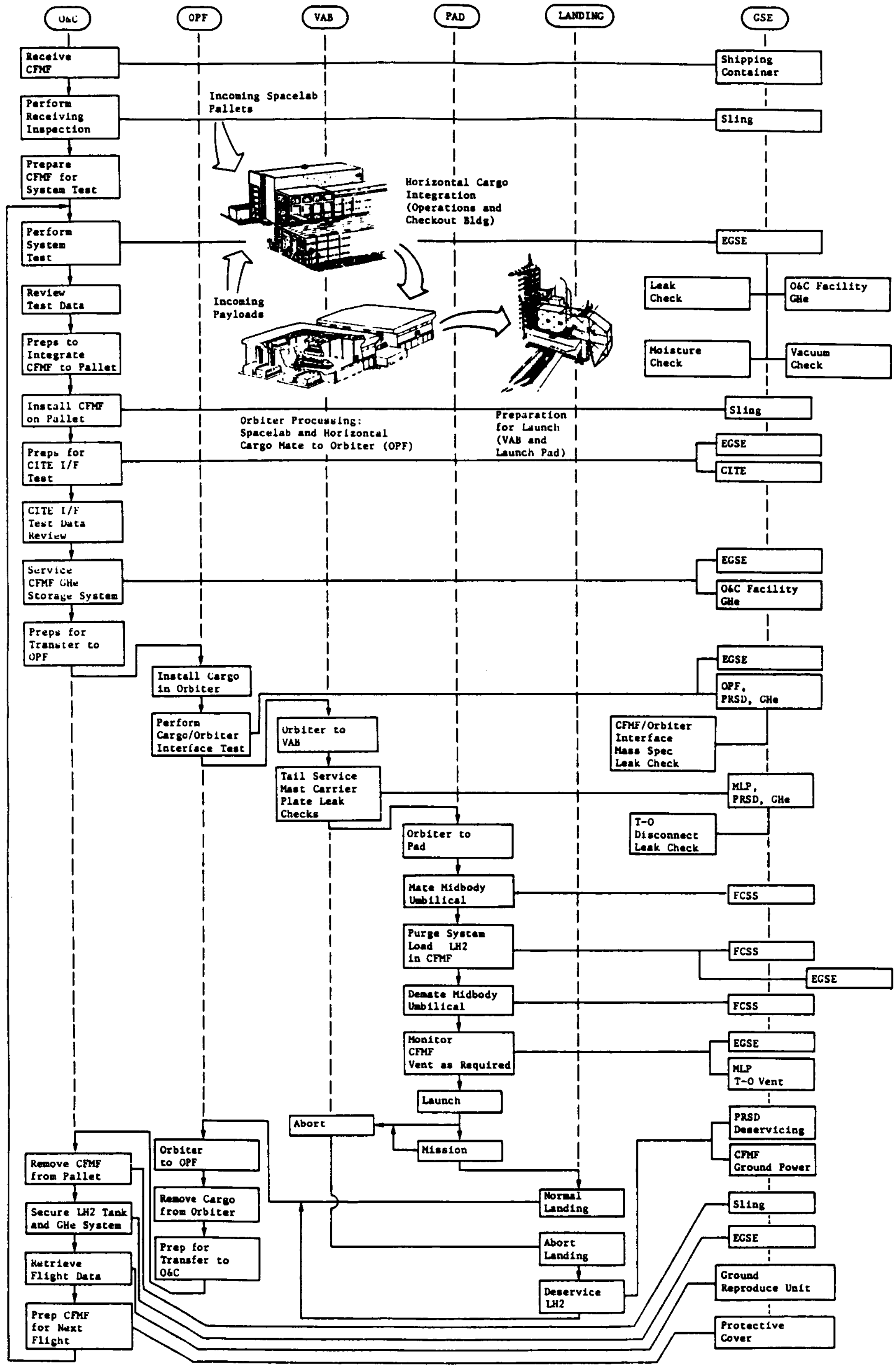



*Figure IV-7 Processing Flow at KSC*

All required support subsystems (FMDM, PCB, etc.) are standard accommodations for either the MDM pallet or MPESS. Since the Orbiter is manifested based on a minimum allocation (of Orbiter resources; length, power, cooling, etc.) of one quarter cargo bay, the manifesting opportunities for the MDM pallet and MPESS are identical.

Other Considerations - Conceptual design studies indicate that the technical objectives of the CFMF can be met on either carrier. Both recommended receiver tank sizes can be accommodated on either carrier; however, mounting of the larger receiver tank on the MPESS would necessitate locating the pressurant bottles on the sides of the truss in a more complex wrap-around structural configuration than is required for the pallet. There are no differences in STS safety requirements or hazardous operation procedures between the two carriers. Documentation and requirements specifications are more mature for the Spacelab/MDM pallet systems than for the MPESS.

The possibility of using residuals within Orbiter subsystem lines or tanks was investigated, and it was determined that the cost to process drawing changes to Orbiter hardware would far outweigh the costs of procuring separate pressurant tanks. Also, there is a reluctance to modify any Orbiter hardware for payload usage. Separate pressurant bottles were therefore baselined for providing gaseous hydrogen and helium for pressurizing and inerting the supply and receiver tanks.

## D. ROM COST AND SCHEDULE

A preliminary schedule for the development and flights of the CFMF is presented in Figure IV-8. A supply tank test article (TA) and flight supply tank are included, as are 3 receiver tanks, the large 0.28 scale tank designated as receiver tank 1 on the schedule, and the 0.18 scale tanks designated as receiver tank 2 on the schedule. The two 0.18 scale receiver tanks would be fabricated simultaneously; final welding of the tank for mission 3 would occur immediately after the flight of mission 2 to allow any last minute changes to be incorporated. The flight schedule assumed a mid-1987 first flight with reflights on a 6-month time interval.

A ROM cost estimate was prepared against this schedule and the CFMF/carrier conceptual designs to ascertain any cost drivers that would influence selection of the recommended design approach. Delta cost differences we were able to identify between the two carriers did not exceed two percent of the total costs and therefore were not considered significant in solely deciding which carrier was preferred.

## E. TRADE STUDY RESULTS

An evaluation of all carrier trade studies has resulted in the MDM pallet as the recommended CFMF carrier. Table IV-4 summarizes the trade study findings. It was concluded that either carrier would be acceptable; however, the increased complexity of the CFMF/MPESS structural interface, thermal isolation design, and systems integration makes the MDM pallet the preferred choice.

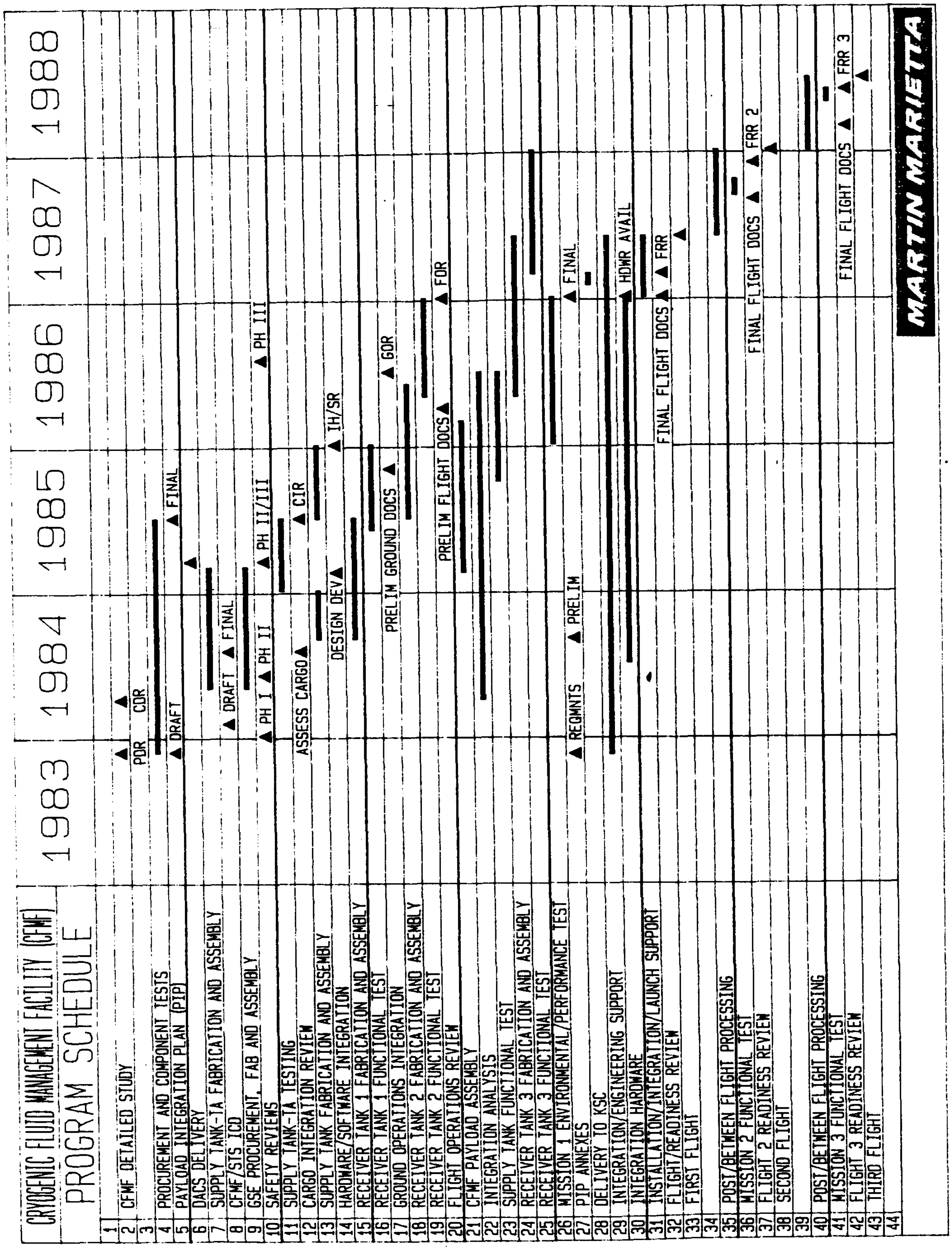



*Figure IV-8 Program Master Schedule*

*Table IV-4 Carrier Trade Study Summary*

| | MPESS* | MDM Pallet* | Remarks |
|---|---|---|---|
| Preliminary structural analysis | | X | CFMF/MPESS interface more complex |
| Preliminary thermal analysis | | X | Better thermal isolation and simpler thermal blanket design for spacelab pallet |
| Systems concept definition payload elements, supporting subsystems, standard vs. non-standard accommodations | X | X | Accommodations same for both |
| CFMF/GSE/Shuttle integration complexity | | X | All flights on MPESS would have to be on same S/N carrier. Interfaces, specs not as well defined for MPESS |
| Availability of flight opportunities | X | X | Manifesting and flight costs same |
| Satisfying CFMF technical objectives | X | X | Tech objectives satisfied |
| Facility processing and operations, safety and mission reqmt's | | X | Installation and integrition at KSC more costly for MPESS |
| ROM cost and schedule for development and three flights | | X | MPESS slightly more costly with greater development risk |

* Preferred carrier; if both checked, there is no clear preference.

## V. RECOMMENDED CONCEPTUAL DESIGN

The recommended CFMF conceptual design includes the following:

- CFMF on the MDM Pallet Carrier
  An isometric sketch of the recommended CFMF package which will interface with the pallet is shown in Figure V-1. A thermal insulation blanket shroud will likely be required to cover the CFMF, pending manifesting and more detailed thermal analysis. Facility active thermal control is required, and tie-in to the freon cooling loop for the pallet avionics subsystems is the recommended approach.
- Scaled Receiver Tanks
  The receiver tanks will be cylindrical vessels with eliptical ends (L/D = 1.39) scaled to the Boeing space-based OTV (Aero-assist concept). Three different receiver tanks with the following scale factors are recommended for the three missions currently being planned:
  - First mission, 0.28 scale, without acquisition device
  - Second mission, 0.18 scale, without acquisition device
  - Third mission, 0.18 scale, with refillable partial acquisition device.
- Receiver tank longitudinal axis along Orbiter x-axis.
- Use of Gas Bottles for Pressurant Storage
  Storage of gaseous hydrogen and helium in separate pressurant bottles for pressurizing and inerting the supply tank and receiver tanks is preferred to using residuals within Orbiter subsystem lines or tanks.
- The CFME Tank Assembly (NASA CR-165496) as the preferred supply tank.

The following MDM pallet elements are considered standard accommodations, to be provided from the inventory, which are part of the recommend conceptual design:

- Power Control Box (PCB) - Distributes and controls electrical power for pallet-mounted experiments and other pallet subsystems.
- Thermal Control Subsystem (TCS) - Provides thermal control of the elements of the MDM pallet, pallet subsystem equipment and payload equipment.
- Flexible Multiplexer/Demultiplexer (FMDM) - Provides command and data handling for subsystems and experiments, and acts as a data acquisition, distribution and signal conditioning unit.
- Payload Timing Buffer (PTB) - A buffer amplifier providing timing signals from Shuttle master timing unit - Greenwich Mean Time (GMT) and mission elapsed time (MET).
- Junction Box - Provides interface between pallet subsystems measurement sensors, PCB and FMDM.
- Pallet Power and Signal Cables
  - standard mixed cargo harness (SMCH) port tray - signal cables
  - payload pallet integration hardware (PPIH) - starboard tray - power cables.

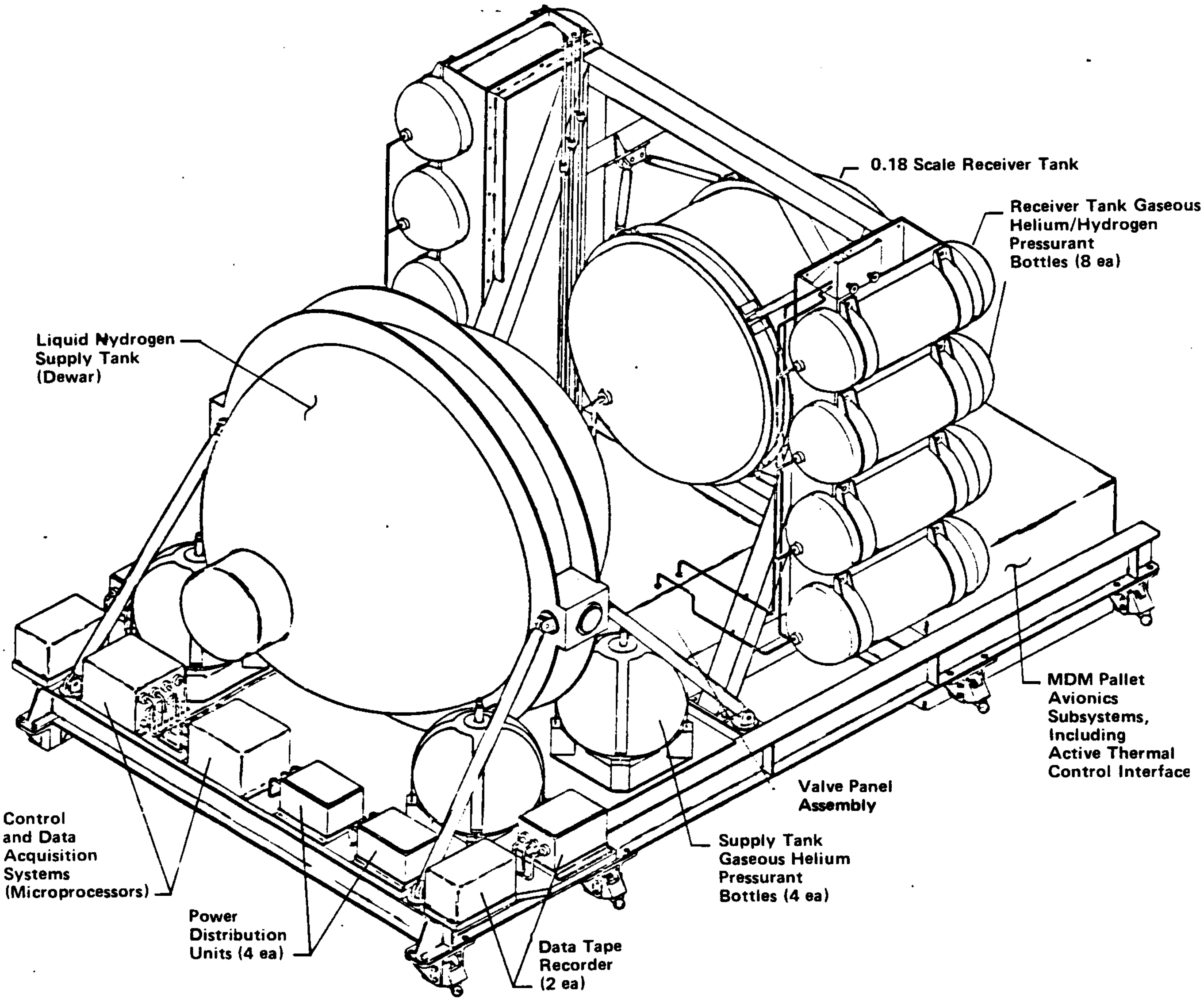



*Figure V-1 Recommended CFMF Conceptual Design*

Required GSE and test equipment to interface with and verify the combined CFMF/MDM pallet includes, but is not limited to, the following:

- Ground cooling cart (active thermal control system checkout)
- Payload special test equipment (PSTE)
  PCB and PTB simulators
- Payload integration test set (PITS)
  General purpose computer (GPC) and MDM drive used to control and monitor thermal control system in ground test (only 2 in inventory - used in CITE stand)
- Special carrier mock-up for structural test (static, modal survey) and/or buildup to verify hardware fab/assembly tolerances, attachments, etc.

Several additional recommendations resulted from the Task I-Concept Definition Task.

- A coupled-loads analysis should be performed to enhance design verification and minimize the risk of integrated Orbiter/CFMF coupled analysis (6-months pre-flight) identifying structural problems late in the processing cycle.
- Extended experimentation beyond the current three-mission planning should be pursued. This considers a possible fourth mission with a baffled receiver tank for investigating the thermal and fluid effects of slosh control fluid management, and an extended (e.g. 6-month) mission attached to the space station or an unmanned platform for investigating longer-term low-g space fluid management technology issues.
- Receiver tank chill and fill tests should be conducted prior to integration into the CFMF.